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Spacecraft Transmitter Reliability

FOR REFERENCE

NOT TO BE TAKEN FROM THIS ROOM

*Synopsis of a workshop
held at NASA Lewis Research Center
Cleveland, Ohio
September 25-26, 1979*

NASA

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sponsored by NASA Lewis Research Center
and the U.S. Air Force and held at
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PREFACE

When the NASA Lewis Research Center became the lead center for space communications, we decided that, to best advance technology, it would be a good idea for representatives of Government and industry to discuss what is known about the reliability of spacecraft transmitters and what is not known but should be. A workshop was held at Lewis on September 25 and 26, 1979 and was well attended by representatives of the aerospace industry and by NASA and Air Force personnel. The participants did not submit formal papers, but many attendees requested some sort of printed memorandum of the workshop.

What follows is a synopsis of the presentations derived from audio tapes of the workshop. In some cases, when the authors made extensive use of graphics and did not supply copies, the abstraction is extreme. The authors have not had the opportunity to review the summaries. If their views are misrepresented, the fault is mine. In most cases of questions or comments from the floor of the auditorium, the speaker is not identified, in keeping with the spirit of the discussion. What follows captures, I hope, the essence of the workshop, but it is not a verbatim transcript.

Erik S. Buck, Major, USAF
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Editor

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OPENING REMARKS:

Joseph N. Sivo, Chief, Communications & Applications Division, NASA-LeRC:

He reminded the audience that we would want to recap, to assess the information presented, and to layout a program to get to the generic problems of TWTs.

Dr. John M. Klineberg, Deputy Director, NASA-LeRC:

NASA Lewis has been involved with space communications technology since 1967, but recently has assumed lead responsibility in this area. The requirement for power amplifiers, including TWTs, and the need for high reliability at low cost will place significant demands on the technical community. We hope to build a relationship with the TWT user community, a technical interchange, which is mutually beneficial and will lead to a definition of new technology endeavors.

Daniel J. Shramo, Director, Space Systems and Technology, NASA-LeRC:

He was pleased to see 31 different organizations, government and industrial, represented at this workshop. Lewis' product is new technology, developed in association with an applied science effort. This is done in partnership with other government groups and with American industry with the goal of producing a technical capability in communications which is superior to that in the rest of the world. Our role is to be a source of high-risk venture capital, looking at long term national goals, 5-10-15 years out, which would be beyond the normal industrial planning cycle. We want to do development planning with the entire communications industry, determine a consensus on the most critical problems. We at Lewis can provide a forum, neutral ground, where industry can come together for useful exchanges of information, yet competitive interest can be protected.

We must be technically competent to carry out a program with a balance of in-house work and industry/academic work. We want to transfer these technology developments to industry at large, by various methods, including workshops like this one. This is a pathfinder conference, the first we have sponsored under our new responsibility for communications technology development. We plan to use such workshops as a major element of our technical development programming. This workshop can serve as a model, teaching us how to work together.

Robert Alexovich, Chief, Communications Technology Branch, NASA-LeRC:

Mr. Alexovich was moderator for the first session. The purpose of the session was to try to provide a view of the users perspective and experience with space transmitters.

SESSION I - USERS' EXPERIENCE WITH SPACE TRANSMITTERS

Richard Swartley, GE, Space Division, Valley Forge, PA: "A User's Perspective on Reducing Risks in TWTs."

His perspective is based on experience with five GE spacecraft and subsystems:

1. Landsat, using 20W S-band TWT.
2. Skylab, S-193 Scatterometer-altimeter-radiometer, using 20W cw helix and 2000-watt helix pulsed Ku band TWTs.
3. Japanese Broadcast Satellite, BSE, using 1-watt driver and 100-watt coupled cavity Ku band TWTs.
4. Seasat scatterometer, using a version of the BSE TWT.
5. DSCS III, 10 and 40-watt helix X-band TWTs.

He also had a good flight experience with TWTs, but the long development cycle of TWTs is an area of critical schedule path. Problems are traceable to definable causes; specifiers and users share responsibility with manufacturers for both the causes and the remedy. Some observations as to causes: the introduction of new technology, the result of demands for higher frequency, higher power, and better efficiency, leads to new materials, new fabrication techniques and processes without adequate funding for developing necessary controls and process verification. Competitive procurements lead manufacturers to try to minimize risks and to hold the costs of reliability verification down. It is encouraging to see the military and NASA sponsoring work on reliability.

Another factor is the long cycle, more than 2000 hours, required to verify each iteration of a design change. There is a need for R&D funding for the development of accelerated life testing of individual components and processes.

The purity and control of materials and processes are more critical than inspection after the fact. There is inadequate investment in facilities for process control and incomplete information on tolerable levels of contamination.

A TWT is an assembly of parts. There is a lack of uniform application of the doctrine of screening all parts, not just inspecting the resulting assembly.

There is over reliance on a small fractional yield, which is often unpredictable. The output is often skewed due to systematic problems. We need to stimulate investment on the part of manufacturers in producibility engineering, material and process controls, and the training and control of operators. There is an economic trade-off between a lot of starts (with low yield) versus investment in equipment and improved process and operator controls.

Schedule constraints and the preoccupation with electrical performance tend to delay environmental performance verification. This leads to failures and chain reactions of problems with changes and schedule delays--all of this compounded by paperwork. Test early. Don't leave mechanical design requirements until the flight hardware stage.

Finally, there is a need to recognize the tendency to specify TWT performance with less margin than is customary with other subsystems. Margin and reliability are closely linked.

Q: Overview of kinds of failures on GE programs and how you got around them?

A: Industry has been outstanding in achieving rf performance and efficiency. The difficulty has been in achieving the producibility and reliability of end items--process control, material contamination. The usual solution is after a crisis has occurred. There is a need to anticipate and prevent problems.

Q: Were the problems cleaned out?

A: No new problems as a result of orbital failures--almost uniformly distributed up to actual integration tests at the vehicle level.

Q: What kind of failures and how many?

A: Mechanical failures in shock environment, both cathode and collector structures. Broken ceramics. Contamination--cathode substrates, particle contamination. High voltage failures, primarily in potting and its adhesion. Cathode life problems due to mysterious things.

Q: (Inaudible)

A: The ones we find after initial screening are only those associated with spacecraft environments and long life. As a result, over the years we've been increasing the time spent in acceptance testing.

Q: (Inaudible)

A: We've had a good experience in orbit, no proven failures due to the TWT. We've had some where we can't separate power supply and tube. Landsat programs, five-year mission lifes, no problems at all.

Q: How many hours to burn in?

A: DSCS program 2500 hours of test, plus 300-400 hours on top of that. Problem of thermal-vac testing. Just ambient testing will not bring out all the failure mechanisms.

Paul Koskos, COMSAT: "Intelsat IV C-band Transmitter Wearout Statistics"

I'd like to call for the next symposium on transistor P.A. reliability.

Intelsat IV, seven satellites, 1971-1975. Twelve operating TWTs on each satellite, 84 for initial population. Twenty failures as of this report. After the fourth year, because of battery degradation, we cycle tubes off during the eclipse season, at this time, about 40 cycled, 40 uncycled. In the uncycled population, there have been three failures, all early in life, approximately 40,000 hours, and none since. In the cycled population, roughly 15 failures, at 50,000 to 80,000 hours. There were four failures which we attributed to the EPC, the current went up; recently we have considered the possibility that these were also tube failures. The majority, 18 out of the 22, there was a gradual degradation in current, a decrease in gain.

A cumulative failure plot (on the 18 failures) shows a mean life of 7.8 years and a standard deviation of two years. There have been only two failures out of 12 in F-2, the satellite that has run the longest (8 years). Until now, there have been no channel failures because each tube had a backup tube. We have been fortunate in getting this much life; I don't know why.

In the 40 or so tubes which have continued running uncycled, for up to 8 years, there have been no failures since the 40,000 hour point. There are enough failures in the cycled population to raise a question whether you should not design a satellite so that you don't need any cycling.

A Monte Carlo analysis, a model, shows a first channel failure at about 8 years of operation and 50% failure at about 15 years.

Q: How do you detect failures?

A: We have two busses. A change in bus current warns us; we can make rf tests, measure gain. Several times we have turned all the tubes on a bus off, one at a time, looking at the change in current. Laboratory tests have measured the change in gain with change in current. It correlates.

Q: Were the tubes cycled off for the entire eclipse season?

A: Yes, one or two months, twice a year.

Q: The no failures after 40,000 hours on uncycled tubes doesn't seem to fit with your statement that you began cycling after four years to save the batteries.

A: We cycle some of the tubes off. We have spare capacity. The extra tubes are cycled off. Between four and six tubes have been kept continuously on.

Q: What sort of prediction of mean life have you been able to get from the uncycled population?

A: We aren't having enough failures to make a significant prediction. There are only about five uncycled tubes at the long life end of the chart--80,000 hours.

Q: The life test tubes that you must have at Hughes, have they been cycled on and off?

A: I'd rather let Hughes answer that.

Comment from floor: To my knowledge, there are no Intelsat IV tubes on life test. There is no life test base of the 261H TWT.

KOSKOS: We have run three early tubes at the labs in a simulator, and there have been a lot of on-off cycles on that. We think we have perhaps 30,000 hours with no failures.

Q: Are the redundant TWTs powered?

A: No

Q: Have you correlated failures you attributed to cycling with tubes which have been in storage in orbit?

A: We have switched on some 13 back-up tubes; there have been no failures. They were unaffected by four or five or six years of shelf life in space, and I don't know how many years on the ground.

Q: How do you define failure?

A: The simple kind is when you turn it on and there is no current. The complicated kind is where there is a gain degradation, a number of dBs.

Q: Do your data show whether the cycling related failures were catastrophic or degradation?

A: It's in the data. We have assumed it was just a wearout. We have to review that data; I don't have that number right now.

I'd like to acknowledge that all of this work at COMSAT was done with the support and encouragement of the INTELSAT organization which operates the satellite system.

EDITOR'S NOTE: Recent work at NASA-Lewis has shown that 95-98% of the tube beam power can be recovered by a good multi-stage depressed collector (MDC) during periods when there is no rf drive (or output). Hence, it may be practical to leave tubes on, but not amplifying, during the eclipse periods.

Major Chandler Kennedy, SAMSO: "Reliability of Space TWTAs - The Military Experience."

(Reader should check accompanying "visuals")

We are not, in my organization, the Advanced Space Communications Directorate, a customer or a user. We try to anticipate requirements and provide advanced technology programs, with a viewpoint into the 1990's. We see a movement to higher frequencies and higher powers with more reliability. (Gaps because of tape change.) Mean life requirements have extended from 1½ years for a 3-watt X-band satellite up toward 7 years for a much more complex system.

Here is a chart, based on nineteen 20-watt TWTAs on DSCS II and NATO III satellites. We've had two infant mortalities, one only lived for 7 minutes. The rest have indicated a mean life of about 3½ years, so this is what I expect out of the future high-power tubes based on the same technology.

These failures (from a larger population) have occurred preferentially during the eclipse season and about a month afterwards. This is consistent with other kinds of satellite failures. There is a relatively high stress on the whole spacecraft.

In the near future, we are looking to deploy the DSCS III satellite, with four 10-watt channels (three tubes for every two channels) and two 40-watt channels, with a redundancy of two for each channel. Based upon TWTA failures alone, we reach a mean life of about 5 years if the mean TWTA life is 3.5 years, extrapolating from the 20-watt experience.

Basically we have a sudden death rather than a wearout. The tubes switch themselves off, possibly a circuit breaker malfunction, but more likely a high voltage breakdown because the breaker trips when the high voltage supply turns on. This has been the dominant failure mode.

On the ground, we've seen breaker trips with collector or gun arcing. We detect helix current spikes when this occurs. In ambient testing, we saw no arc-overs. The atmosphere prevents them. In subsequent thermal-vac testing we had 50% failures almost immediately to these arc-overs.

I'd like to cover what we think is the rational thing to do. We need to address the technology base, production problems, and a schedule anomaly for spacecraft programs. We'd like to explore controlled porosity dispenser cathodes as an alternative to current oxide cathodes, and field emission arrays. New types of power supplies and new approaches to high voltage isolation.

We feel the current technology base for TWTAs is extraordinarily narrow. Our program will be screening promising new technologies. We are concerned about a lack of interest in tubes as compared with solid state. We have few vendors.

In the production area, troubles plague us. You can't tell the good TWTAs; it is not known what the proper screening procedures are. Accelerated life testing is infeasible, but some life testing is necessary for TWTs, particularly the new ones.

I'd like to illustrate that there is a schedule anomaly. I think you have to perform a life validation on these tubes, in the kind of environment that you expect to see in the spacecraft. If you develop a custom tube, starting the TWTA after you have a specification for the TWTA system interface, you don't have time for a life validation. If you wait for the results of the life validation program, you have to start development of the TWTA before you have a system design. You have to make the system fit the tube. I believe we're going to have to develop TWTAs in anticipation of the system, and the system will have to use whatever has been developed.

Solid state alternatives to TWTAs have some significant advantages. Accelerated testing and screening at the piece part level allow accelerated development. We could use large active arrays with each element having its own solid state amplifier. Their global implementation as TWT replacements will be prevented by their limitations. (Ref. vu-graph "Solid State Alternatives"). The active arrays have a programmatic difficulty. Their lower efficiency will impact on the power system.

(Discussion of "Recommendations for TWT Development"). We'd like to see the use of common developments for civil and military applications. I think the first opportunity for this is at the 20 GHz band, where the civil and government bands are adjacent. Some production problems are due to the irregular on-again, off-again production of TWTAs. I think once you determine your needs, at least produce the tube with a level production rate.

Q: Have there been attempts to compare civil and military failures?

A: It's been thought about, but no large effort has been made. Largely we have very contrasting failure modes.

Q: Is there a battery conservancy regime you go into which might accelerate the failures?

A: There's no dumping of the load during eclipse. The first suspicion would be that it's a thermal cycling effect. On the ground, the downward swing of the thermal cycle is related to the arcing. The arcs tend to disappear at the higher temperatures.

Q: Where were the arcs in thermal-vac?

A: That data is so fresh that we have no data analysis other than noting that they have arc signatures.

Q: Where did you use SF₆ cover gas?

A: We don't have experience with it, but I'm suggesting it might be helpful. It would protect the TWT during critical pressures and then could be vented to space, leaving a hard vacuum.

Q: Re: recommendation of voltage multipliers, does this take into account the large number of diodes required? Hardware trade-offs?

A: We haven't studied diode reliability. The high voltage transformer is a potential failure source because of high voltage stress. Also, it is a long lead item; anything to shorten the production time would help the schedule problem.

Q: Do you use an oxide cathode?

A: Yes.

Q: Re: sudden high voltage failures. Are these recoverable?

A: Very few have been recoverable. One we left off, after one attempt to restart it, so that if there was a void in the potting, it could outgas. The tube was turned back on successfully. It operated for a few hours and switched off. So it is partially recoverable, apparently, but not in realistic sense.

Q: Why the differences between military and civilian failures?

A: Military Comsats are using X-band. The tubes are smaller, generally, and they are operating at higher power.

COMMENT: High voltages are more than twice what they are commercially.

A: Yes. But one could design so that the field stress is the same.

COMMENT: Your chart, "The Trouble with TWTs is..." For power FETs, you could use the same chart, including accelerated life testing. (Laughter) There are certain things you can find out in accelerated life testing with FETs, and there are some things which don't show up. A lot of the infatuation with solid state exists because people just aren't familiar with the problems. There are long cycle times in production. We have run solid state experiments in space. There are problems with high power, high frequency. I don't think we should all rush to solid state next year.

A: That point is well taken.

Q: Is there a contradiction in your statement that we need a broader technology base for tubes, but we should go to solid state as soon as possible? Can that happen with limited resources?

A: I don't think solid state can meet all the requirements. The most you can get is very high reliability amplifiers in the (low power, low frequency) corner of the diagram. You're going to have to develop TWT technologies, because there is no reasonable solid state alternative in most of the rest of the frequency-power space.

COMMENT: If I may shed a little light on the failures that we had on the thermal-vac testing of the 20-watt DSCS life tube. What we did was take four amplifiers which had been running since 1971 with a clear record (there had been two other failures for probable leaks). We took these, put them in a thermal-vac test over the acceptance temperature range of about 60° to 146°. Two failed of those four within the first few days,

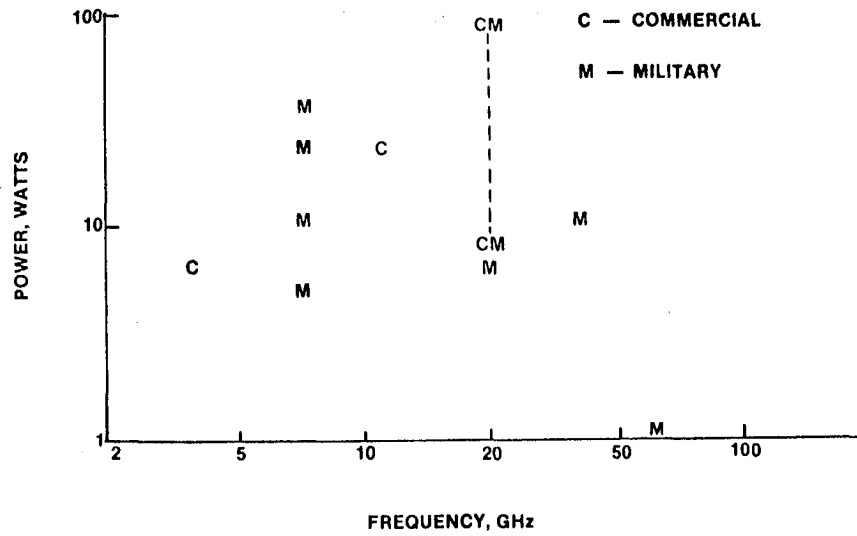
and failed at high temperature. They also failed on restart at high temperature. We found we could run them at up to 100^o, as long as we switched them off before the cycle got to the hot side. The other two have run for 3½ weeks, though they have had some of what we call arc signatures.

Q: The report of that test data is contrary to what you saw in space, at cold temperature?

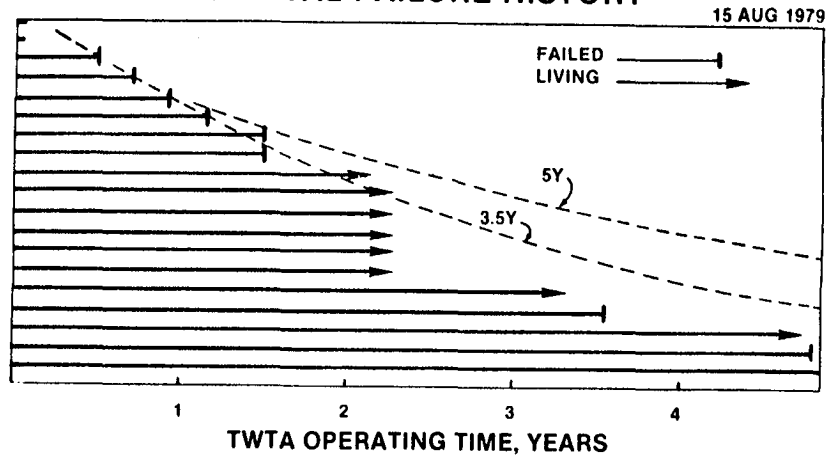
A: That's not known. That was in some of the thermal-vac screening that was done 1½ - 2 years ago. (Inaudible remarks from the floor.)

COMMENT: That's par for the course. If you are having high voltage arcing problems, you can have them any time--hot temperature, low temperature. You have a design problem.

TRENDS IN COMSAT AMPLIFIERS



20 W TWTA ORBITAL FAILURE HISTORY



JAN	FEB	MAR	APR	MAY	JUN
JUL	AUG	SEP	OCT	NOV	DEC



FAILURE DIAGNOSIS

- 0 (SPACE) SUDDEN SWITCHOFF, FAILURE TO RESTART AFTER HEATER TIME-OUT DUE TO BREAKER TRIP OFF
 - CKT BREAKER MALFUNCTION ?
 - HIGH VOLTAGE SHORT IN TUBE OR EPC ?
- 0 (GROUND, HI-POT AND T/VAC SCREENING)
BREAKER TRIPS DUE TO COLLECTOR OR GUN ARCOVER. HELIX CURRENT SPIKES INDICATE PARTIAL DISCHARGES.
- 0 (GROUND, AMBIENT LIFE TESTING)
NO FAILURES TO ARCOVER AFTER SIX YEARS CONTINUOUS
- 0 (GROUND, SUBSEQUENT T/VAC TEST)
50% OF SAME TWTAS AS IN PREVIOUS TEST FAILED

PLANNING FOR TWTB DEVELOPMENT

- 0 TECHNOLOGY BASE
- 0 PRODUCTION PROBLEMS
- 0 TYPICAL SCHEDULE

SPACE TWT TECHNOLOGY BASE

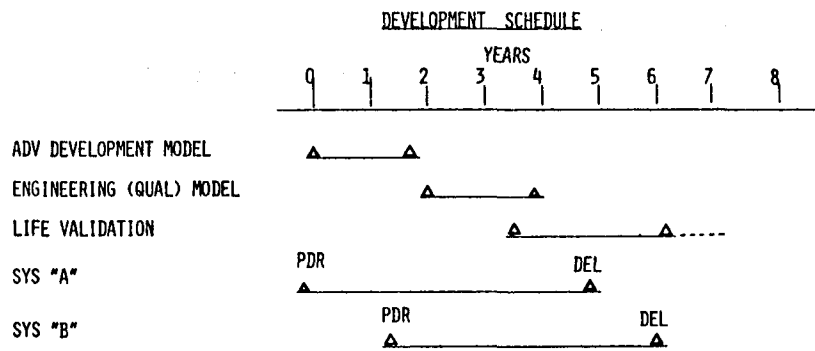
<u>CURRENT</u>	<u>FUTURE</u>
CU-CLAD W-HELIX	RING-BAR
BN, BeO SUPPORT RODS	DIAMOND, SINGLE XTAL BeO
OXIDE CATHODE	W-MATRIX, CPD, FEA
SINGLE, DUAL DEPRESSED COLLECTOR	MULTIPLE DEPRESSED COLLECTORS
	CAPACITOR - DIODE
EPCs USING HI VOLTAGE TRANSFORMER	VOLTAGE MULTIPLIER
HIGH VOLTAGE SILICONE-BASED POTTING AND URETHANE	FLEXIBLE EPOXY, UNPOTTED TWT, SF ₆ COVER GAS

TECHNOLOGY APPROACH TO TWT IMPROVEMENT

- PREMISE: 1985 SYSTEMS REQUIREMENTS FOR POWER AMPLIFIERS CAN'T BE MET BY 1965 TECHNOLOGY
- OBJECTIVE: EXPAND TWT TECHNOLOGY BASE FOR INCREASED PERFORMANCE, RELIABILITY AND MANUFACTURABILITY
- CRITERIA: EXPLORATORY DEVELOPMENTS WILL BE ENCOURAGED AND SCREENED FOR HIGH PAYOFF TO SPACE TWTAS. FEASIBILITY TO APPLICATION MUST BE DEMONSTRATED BEFORE ADVANCED DEVELOPMENT COMMENCES
- APPROACH: ADVANCED DEVELOPMENT MODELS WILL BE DESIGNED AND FABRICATED INCORPORATING NEW TECHNOLOGY. TESTING FOR INITIAL PERFORMANCE AND LIFETIME CONFIDENCE WILL BE DONE ON ADH'S AND AT SUBCOMPONENT LEVEL.
- CONCERN: LACK OF COMMUNITY INTEREST IN VACUUM TUBE TECHNOLOGY

" THE TROUBLE WITH TWTAs IS . . .

- A. THEY TAKE EIGHTEEN MONTHS TO MANUFACTURE."
- B. THEIR YIELD RATE IS DIFFICULT TO PREDICT."
- C. YOU CAN'T TELL THE GOOD GUYS FROM THE BAD."
- D. ACCELERATED LIFE TESTING IS INFEASIBLE."
- E. ALL OF THE ABOVE."



WHY NOT SOLID STATE ?

ADVANTAGES:

- O ACCELERATED TESTING ALLOWS REDUCED DEVELOPMENT TIME
- O BETTER RELIABILITY
- O ACTIVE ARRAY FEASIBLE
- O NO HIGH VOLTAGE POWER SUPPLY

SOLID STATE ALTERNATIVES

DEVICES (LIMITATIONS)

- GaAs FET (LOW POWER, LOWER EFFICIENCY, FREQUENCIES LESS THAN 20 GHz)
- IMPATT DIODES (LOW POWER, LOWER EFFICIENCY, SATURATED OPERATION)

AMPLIFIERS (LIMITATIONS)

- CIRCUIT POWER COMBINERS (LIMITED CAPACITY)
- SPATIAL POWER COMBINING ANTENNAS (NO TWT REPLACEMENT)

CONCLUSION

- SOLID STATE REPLACEMENTS FOR TWTAS ARE NOT UNIVERSALLY AVAILABLE IN FORESEEABLE FUTURE. TWTAS WILL BE NECESSARY FOR APPLICATIONS WHICH DEMAND HIGH FREQUENCY, EFFICIENCY, AND POWER. SPECIFICALLY, AT X-BAND, 10 W CAN BE REPLACED ENTIRELY ONLY IF POWER SYSTEM CAPACITY IS INCREASED; 40 W CANNOT BE REPLACED WITHOUT MAJOR REDESIGN OF SPACECRAFT.

SOLID STATE AMPLIFIERS

OBJECTIVE

- REDUCE RISK OF IMPLEMENTATION IN CURRENT AND PLANNED SYSTEMS
- PROVIDE PERFORMANCE COMPARABLE TO TWTAS

APPROACH

- IMPROVE BASIC EFFICIENCY OF DEVICES
- PROVIDE RELIABILITY DATA ON IMPROVED DEVICES
- DEVELOP MODULARIZED POWER AMPLIFIER
- DEVELOP POWER COMBINING ANTENNA SUBSYSTEM

CONCERNS

- GAAS MATERIAL QUALITY CONTROL
- INDUSTRY DRIVING FOR HIGHER POWER ONLY
- DIFFICULTY OF "TECHNOLOGY TRANSFER"

RECOMMENDATIONS FOR TWTAs DEVELOPMENT

- 0 DESIGN SPACECRAFT TO ACCOMMODATE TWTAs
- 0 LONG-LEAD DEVELOPMENT / VALIDATION OF TWTAs
- 0 EXPAND TECHNOLOGY BASE
- 0 USE COMMON CIVIL / MILITARY HARDWARE
- 0 LEVEL PRODUCTION RATE
- 0 REPLACE WITH SOLID STATE ASAP

Herb Zelen, RCA Astro-Electronics: "RCA Experience with TWITAs"

I'm going to limit discussion to recent experience with commercial satellites. RCA has had experience going back to 1962 with narrow band telemetry amplifiers, but those problems are quite different. They had all sorts of problems, but, while we had failures, they met so-called mission requirements. In the commercial area, we'd like to keep all the amplifiers on forever. We're interested in channel years.

There are two RCA Satcoms, F-1 and F-2, launched about 3½ years ago. They are 24-channel satellites with 24 amplifiers. We thought having 24 channels on one satellite was redundancy in itself, but of course they're all occupied, and we need more channels. Any one failure is a problem for us.

With the F-3 satellite, we learned from experience. We bought all the amplifiers at one time, from Hughes, so they are all the same design. What we did in F-3, which is still in test, we have 28 amplifiers for 24 slots and a great number of coaxial switches, for a 7 for 6 redundancy. The total population of amplifiers we're talking about is 78.

We also built a single satellite, for Telsat of Canada, called ANIK-B, called F-4 in their nomenclature. It has 12 C-band 10-watt amplifiers and 6 K-band 20-watt amplifiers, four of which can be active. It was launched about a year ago. Those amplifiers were bought from Telefunken of Germany, 14 C-band and 6 K-band. So that's the population of amplifiers we can talk about.

On the F-1 and F-2, after the acceptance tests and workmanship problems, in spacecraft ground test--we had no failures.

Of course, we've had several failures in orbit, and a number of anomalies. One kind was where a 3-minute timer recycled, and another was where TWTA protection circuits shut the amplifier down for one fault or another. On F-3, we didn't change the amplifiers. We added an extra amplifier for each group of six, seven for six. We also added an external box which can disable the 3-minute timers in orbit, once we've turned the tubes on. To get those four amplifiers, we've added 48 coaxial switches and all the cables. Five years ago, I don't think we would have considered that kind of hardware trade-off.

In the ANIK-B, during spacecraft test, we had two failures. In the C-band failure, it was CSR-13 capacitor, a standard hi-rel part. It had a fractured lead. In the spacecraft tests, in vacuum, we had a helix current increase and shut-off. It appeared to be a high-voltage failure, but after a great deal of detective work, it was shown to be a microscopic break in the lead in the regulator of the EPC.

With the K-band amplifier, it appeared the helix attenuator was damaged (3rd order intermod was out of spec.), probably during final acceptance test by operating into bad mismatch.

We've had no indications of early failures in orbit, over a year.

In the F-1 and F-2, there were three catastrophic failures: two were infant mortality and the third occurred several years later. We have not seen, yet, gain degradations, only step changes in gain. We can't turn our amplifiers off, so we don't have some of the fine grain information it would be nice to have. We have the 3-minute cycle problem, many times. If we can save even one amplifier with the modification of cutting out the timer, that would pay for itself. There were other anomalies which we corrected by reducing the helix current; we don't know why. We had one amplifier on F-2 which looked like high voltage arcing. We have not had the large number of problems which DSCS has reported. The last two may be mechanical connection problems. All these things eventually correct themselves over a period of time.

The German designers, with new systems, had all sorts of problems which they eventually solved. But it caused a big schedule glitch. We didn't have a real schedule glitch with Hughes Aircraft. We've had workmanship problems. We think you can get rid of them with a combination of designing and screening. Avoid problems like the cold flow of wire. (Gap in tape.)

We've had parts failures in orbit, and with ANIK-B we had part failures even after all this high-rel testing. Materials and processes problems are always with you--people try to make it better but it isn't. "Improved" magnets are an example.

The wearout problems are what we hope we'd down to--cathodes which will last 8 or 10 years. We've seen no indications of wearout in 3½ years. Our last test program isn't 100% successful. If we knew how to do it better, we would. A million dollars a channel a year would not be an unreasonable cost, if we could guarantee we could save one more amplifier, but we don't know what the problem is.

Q: Can you clarify the timer recycling?

A: There's a delay from heaters on to high voltage on. The timer would recycle.

Q: The high voltage was off?

A: Yes

Q: Can you watch trends?

A: All of the 48 channels are active. All of the customers watch them actively, continuously. The telemetry is not very linear. We don't see small degradations rather step changes in gain and in output power.

Q: Then you don't see trends over 3½ years?

A: There are so many anomalies, I think we have several problems. I haven't seen anything that looks like a gain degradation yet.

Q: One of your problems could be alleviated by backing off some channels by about a dB. Are you presently operating that way?

A: Yes.

Q: Has there been on-off cycling?

A: All channels are powered through eclipse. There have been a few cases of on and off to check out anomalies but generally they are on all the time.

COMMENT: The third failure we attribute to shutting the TWT off. It was a one-shot deal where we turned most of the transponders off while we looked at an anomaly, and when we turned them all on, one didn't turn on. There was a 12 dB gain drop.

Q: How many hours do the tubes have on them when you launch?

A: For the Hughes, about a week in vacuum. For ANIK-B, a little longer, to take a lot of data, but the tests are about the same. RCA Satcom satellites are 3-axis stabilized, so the temperature variations may be a little more significant than in a spinner, about 15° on a daily basis. That's about the only environmental difference we can see.

Q: How many hours of burn-in at the subcontractor's facility?

A: One thousand (1000) hours, roughly. As integrated amplifiers, some are delivered with as little as 100 hours on them; with ANIK-B amplifiers, 700-800 hours of spacecraft test.

RCA TWTA EXPERIENCE

RCA SATCOM

F1, F2 24 - C-BAND, 5 WATT TWTA's - IN ORBIT
F3 28 - C BAND, SWATT TWTA's - IN S/C TEST
HUGHES EDD TOTAL = 78 TWTA's

ANIK B

F4 12 - C BAND, 10 WATT TWTA's - IN ORBIT
4 - K BAND, 20 WATT TWTA's - IN ORBIT
AEG TELEFUNKEN TOTAL = 14 C-BAND
= 6 K-BAND

RCA SATCOM

F1 & F2

NO FAILURES DURING S/C TEST

SEVERAL IN ORBIT FAILURES

TIMER RECYCLE

TWTA SHUTDOWN

F3 TWTA CHANGES

REDUNDANT TWTA 7 FOR 6

DISABLE TIMER

ANIK B

2 FAILURES DURING S/C TEST

1 - C-BAND (PART FAILURE: FRACTURED CAPACITOR LEAD)

VACUUM TWTA SHUT DOWN

HELIX TLM INCREASE

1 - K-BAND (TWT HELIX ATTENUATOR)

INTERMOD OUT-OF-SPEC.

OUT-OF-BAND SPUR

TWTA GROUND TEST

FAILURES DUE TO:

DESIGN

WORKMANSHIP

PARTS

MATERIALS & PROCESS WEAROUT

TEST PROGRAM TO WEED OUT FAILURES

NOT 100% SUCCESSFUL

TWTA FAILURES

<u>S/C</u>	<u>DATE</u>	<u>SYMPTOM</u>	<u>PROBABLE CAUSE</u>
F1	2/11/76	OVERCURRENT TURNOFF	INFANT MORTALITY - HV POWER SUPPLY
F2	4/29/76	INTERMITTENT RF - TURN OFF	INFANT MORTALITY - HV POWER SUPPLY
F2	9/13/79	GAIN DROP - 12 DB	TWT TURNOFF THEN ON

TWTA ANOMALIES

TURNOFF - SELF CORRECTABLE OR BY COMMAND

F1	3/15/79	INTERMITTENT LOSS OF HV - CYCLING THROUGH 3 MINUTE WARM UP.	SELF HEALED. NORMAL OPERATION SINCE FEB. 1979 HYPOTHESIS: DEGRADED RESISTOR IN POWER SUPPLY
F1	1/21/79	THREE RF INTERRUPTIONS ON SAME DAY. GRADUAL POWER DECREASE.	NO CAUSE. OPERATING NORMALLY.
F2	1/18/78	HV TURN OFF - ONE TIME CYCLED THROUGH 3 MIN. WARMUP	NO CAUSE. OPERATING NORMALLY
F2	2/28/78 THRU 3/30/78 1/16/79 THRU 2/12/79	TOTAL OF 59 OCCURRENCES OF HV LOSS WITH SELF CYCLING THROUGH 3 MINS. WARMUP	INTERMITTENCE IN POWER SUPPLY, PERHAPS DUE TO SEASONAL TEMPERATURE VARIATIONS.

TWTA ANOMALIES

TURNOFF - CORRECTABLE BY OUTPUT POWER BACKOFF 1 DB

F1	2/17/79	SELF TURN-OFF, COMMAND TURNON	HYPOTHESIS: REDUCED HELIX CURRENT CAUSED IMPROVEMENT.
F2	3/23/78	MULTIPLE COMPLETE TURNOFFS, COMMAND TURNON.	SIMILAR TO ABOVE.

OUTGASSING

F2	2/10/76 THRU 4/78	OVERCURRENT SHUTOFF	NORMAL OPERATION. SELF HEALED HV ARCING IN POWER SUPPLY DUE TO ENTRAPPED GASES.
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GAIN REDUCTION

F1	3/31/79 THRU 9/19/79	STEP DROP IN GAIN 7 - 8 DB	NORMAL OPERATION. SELF HEALED BELIEVED TO BE MECHANICAL CONNECTION
F2	4/29/77 THRU 5/5/77	RF POWER FLUCTUATIONS 2 TO 10 DB	NORMAL OPERATION. SELF HEALED

SESSION II - Cathodes

Moderator: Dr. Ralph Forman, NASA-LeRC

Albert F. Morreall, RADC: "RADC's Cathode Life Test Facility"

The major areas I'll address: the requirement or need for this facility, the objectives, approach, progress to date, future plans, and summary. Also, a brief overview of RADC's other cathode-related efforts.

For the 1980's, we project a need for cathodes with loadings of 1 or 2 amperes per square centimeter and lifetimes of 60,000-90,000 hours, roughly 7-10 years. The oxide-coated cathode is ruled out.

Until recently, little was known about poisoning of coated dispenser cathodes; Jim Cronin's very fine article in this month's edition of Microwave Journal has shed a great deal of light.

Also, the stability of the osmium-ruthenium coating at loadings above $2\text{A}/\text{cm}^2$ was questionable; Les Cronin, also of Spectro-mat, has indicated this is the case. However, at $2\text{A}/\text{cm}^2$, these cathodes are very promising. NASA-Lewis has reported at least one coated 5:3:2 cathode has reached 29,000 hours, and an uncoated 5:3:2 cathode has attained 42,000 hours, with both still going. The possibilities of incorporating osmium or iridium in the body of the dispenser, in the matrix or in the impregnants, are also under investigation. The iridium matrix by Varian appears to have much to offer. Also field-emitters are worthy of attention.

In addition to the emitting materials, cathode performance is affected by matrix porosity, activation schedule, processing techniques and operational environment. Evaluation of these will lead to new or improved cathode designs, which can be adequately evaluated only by life testing.

Our objectives is to establish an in-house facility to evaluate cathodes at 1, 2, and $4\text{A}/\text{cm}^2$, over a long duration, at least 10 years. In the event of cathode failure, an autopsy will be performed. All data will be analyzed with the intent to determine failure mechanisms and evaluate cathode parameters. The choice of cathodes and life-test vehicles is controversial, but was made in the hope of acceptance by the majority of cathode users.

The initial 40 test vehicles will be more or less as shown.

There is an optical windown for temperature measurement and a puncturable membrane for residual gas analysis. The flange (on the left) is $1\frac{1}{4}$ " in diameter. From the base of the gun stem to the end of the collector is about 6".

AC was chosen for the heaters to avoid electrolytic and other chemical effects that tend to cause insulation breakdown when using DC. The cathode voltage can be varied. The first four models will be used and checked out for possibly needed design changes before the other 36 are made. Future vehicles may be simpler, with a non-convergent beam.

The coated 5:3:2 cathode at 4 A/cm^2 is questionable. We may use the coated 4:1:1 which we can operate at a lower temperature. The cathodes will be extremely well documented throughout their manufacture, so as to be of the highest quality and, most important, reproducible.

Both AF Materials Lab and NRL have offered their support in analyses of failed cathodes. Full scale testing should begin around July 1980. During FY 81, we plan to acquire at least 15 more units. We want to include the controlled porosity dispenser cathode by NRL, which has shown 10 A/cm^2 for 4000 hours. We also want to include field emitters and other types as they become available. We want to develop a vehicle in which the cathode can be removed, analyzed, and replaced, all under high vacuum, so as to compare good and poor emitters.

We are applying about \$300K per year, and hope this cathode test facility will benefit all cathode users, in operation for at least 10-15 years, and will be recognized as the national tri-service cathode life test facility. RADC is sponsoring the 1980 Cathode Workshop in April.

Q: Who is manufacturing these cathodes?

A: I cannot say, now.

- o REQUIREMENT
- o OBJECTIVE
- o APPROACH
- o PROGRESS
- o FUTURE PLANS
- o SUMMARY
- o RADC's OTHER CATHODE RELATED EFFORTS

CATHODES FOR MM WAVE TUBES

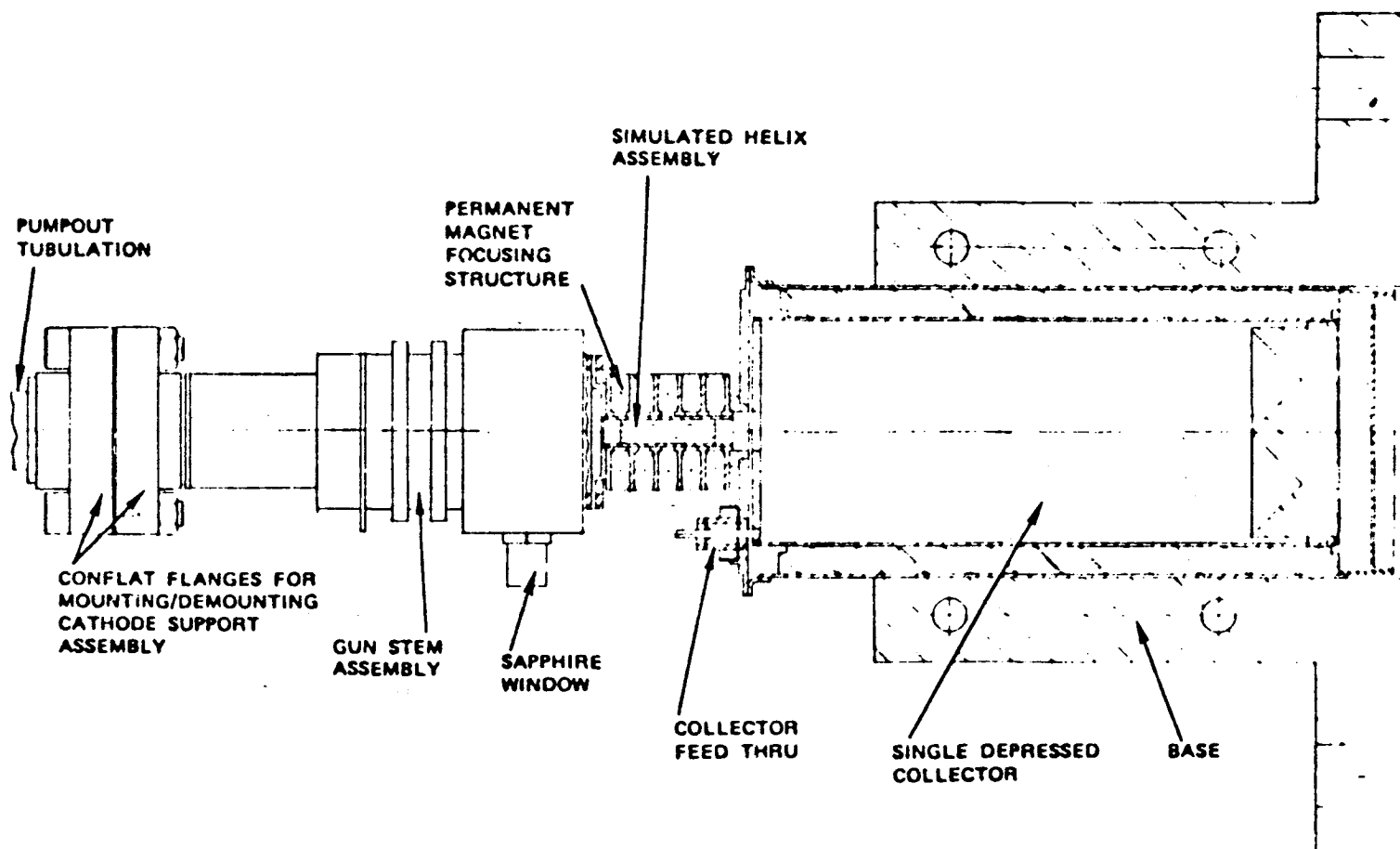
o PRESENTLY AVAILABLE	CATHODE TYPE	J(A/CM ²)	LIFE EXPECTANCY (HOURS)
	o CPC OXIDE	.5	> 10,000
	o VARIOUS DISP.	1	?
	o 4:1:1 DISP.	2	> 20,000
	o COATED 5:3:2	2	> 30,000
o FUTURE REQUIREMENTS			
	o DISPENSERS		
	o FIELD EMITTERS	2 To 4	60,000 To 90,000
	o OTHERS		

OBJECTIVES

- o **DEMONSTRATE PERFORMANCE**
- o **DETERMINE FAILURE MECHANISMS**
- o **ANALYZE RESULTS**

APPROACH

- o **ACQUIRE TEST VEHICLES WHICH SIMULATE TWT ENVIRONMENT**
- o **PROCURE SELECTED CATHODES**
- o **IMPLEMENT FACILITY WITH AUXILIARY EQUIPMENT**



TEST VEHICLE

TEST VEHICLE PARAMETERS

- o CONVERGENT PIERCE GUN
- o CATHODE SURFACE AREA .05 cm²
- o U PERV .52 (APPROX)
- o FILAMENT 6.3 VAC (NOMINAL)
- o PPM FOCUSED DRIFT SPACE, 6 SECTION STACK
- o COLLECTOR DEPRESSION 75%

INITIAL CATHODE TEST MATRIX

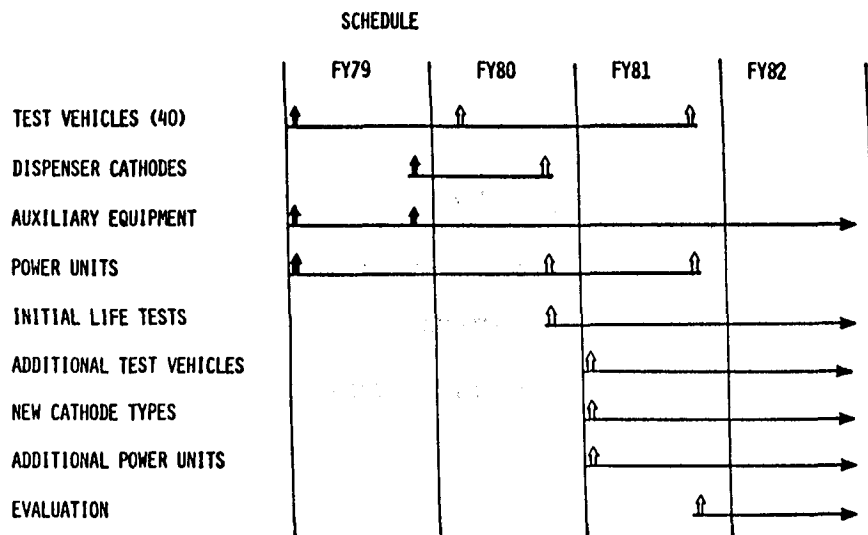
	1 N_{ca}^2	2 N_{ca}^2	4 N_{ca}^2
STD DISP 5:3:2	5	5	
COATED DISP 5:3:2	5	5	5
COATED DISP 4:1:1		5	
COMPOSITE METAL MATRIX		5	5

PROGRESS

- o **TEST VEHICLES**
- o **CATHODES**
- o **AUXILIARY EQUIPMENT**

FUTURE PLANS

- o **ADDITIONAL TEST VEHICLES**
- o **OTHER CATHODE TYPES**



RADC'S OTHER CATHODE RELATED EFFORTS

- o ULTRA LONG LIFE DISPENSER CATHODE STUDY
 - o OBJECTIVES
 - o INVESTIGATE CATHODE DIMENSIONAL INSTABILITY
 - o INVESTIGATE POISONING EFFECTS OF TUBE CONSTRUCTION MATERIALS
 - o DETERMINE EFFECTS OF PROCESSING ON CATHODE ACTIVITY AND LIFE
- o DISPENSER CATHODE PHYSICS STUDY
 - o OBJECTIVES
 - o STUDY EMISSIVE CHARACTERISTICS OF THERMIONIC EMITTER IN GENERAL
 - o RECOMMEND ORDERLY APPROACH FOR DEVELOPING IMPROVED/NEW CATHODE TYPES TO MEET DOD REQUIREMENTS

William Lampert, AFML: "Application of Surface Analysis Techniques to Cathode Failure Mechanisms"

We've shown that a cathode which has been exposed to air and reactivated is not the same as before. Also there are gross differences between the same cathode hot and cold.

The Auger spectrum of a dispenser cathode shows contamination from a titanium carbide grid which evidently sputtered onto the cathode and caused it to lose emission.

The SIMS data, after the fifth sputtering cycle, shows the presence of ytterbium. We don't know why, assume it was not refined out of the barium.

The slide labeled N_{KLL} Auger peak-to-peak height shows a point-to-point look at a collector supplied by Dr. Frank Wachi of SAMSO. It shows a nitrogen contaminant which is consistent with the hypothesis that a leak caused ionized nitrogen to be implanted in the copper by the fields inside the tube.

These give examples of the techniques we can bring to bear. We are willing, within the constraints of the government system, to look at anything that we can.

Q: Has the SAMSO DSCS Office asked you to look at cathodes from some of their life test tubes?

A: I don't really know.

Q: Who can we contact for your services?

A: Any one of us at AF Materials Lab--myself, Dr. Walt Haas, or Capt. Bruce Lamartine. If it's TWT problems, we can look at it.

Q/DISCUSSION: Re: whether DSCS cathodes life is adequate.

COMMENT: (From DSCS Office): These problems we've had with cathodes weren't mentioned this morning, but we have shared our problems between high-voltage arcing and early cathode degradation. We're getting a very low yield from production, which we can weed out, but it's a serious problem.

EDITOR'S NOTE: Subsequent to the workshop, a change in DSCS tube bake-out procedures toward a shorter, cooler bake-out seems to have greatly improved the yield. The hypothesis is that the oxide cathodes were prematurely converted by the bake-out, exposing them to contamination while the tube was still being pumped. The most important tool in the diagnosis of this problem was residual gas analyzer (mass spectrometer) data taken during bake-out and cathode conversion.

SURFACE ANALYSIS

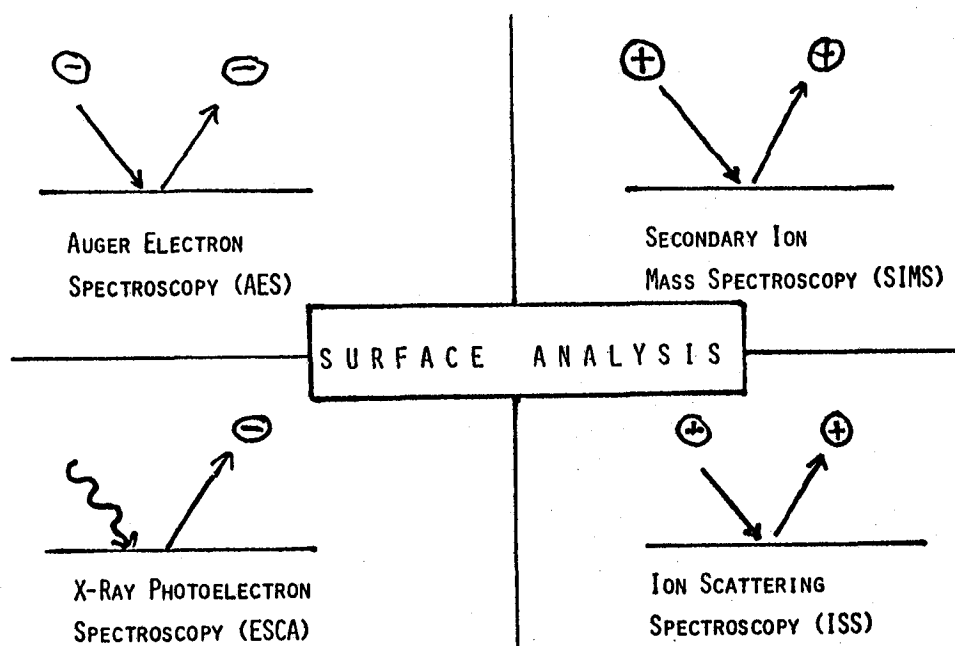
QUALITATIVE ANALYSIS

QUANTITATIVE ANALYSIS

CHEMICAL BONDING

LATERAL DISTRIBUTION

DEPTH DISTRIBUTION



A COMPARISON OF FOUR SURFACE ANALYSIS TECHNIQUES

ADVANTAGES

DISADVANTAGES

ISS

GOOD SENSITIVITY
MAPPING
SEMI-QUANTITATIVE
TOP LAYER SENSITIVE

PEAK OVERLAP
CONSUMES SAMPLE
ROUGHNESS SENSITIVE
MATRIX EFFECTS
NO CHEMICAL INFO

SIMS

ALL ELEMENTS
HIGH SENSITIVITY
CHEMICAL INFO
SEPARATES ISOTOPES
MAPPING

STRONG MATRIX EFFECTS
CONSUMES SAMPLE
PEAK OVERLAP
ORIENTATION, ROUGHNESS
SENSITIVE

ESCA

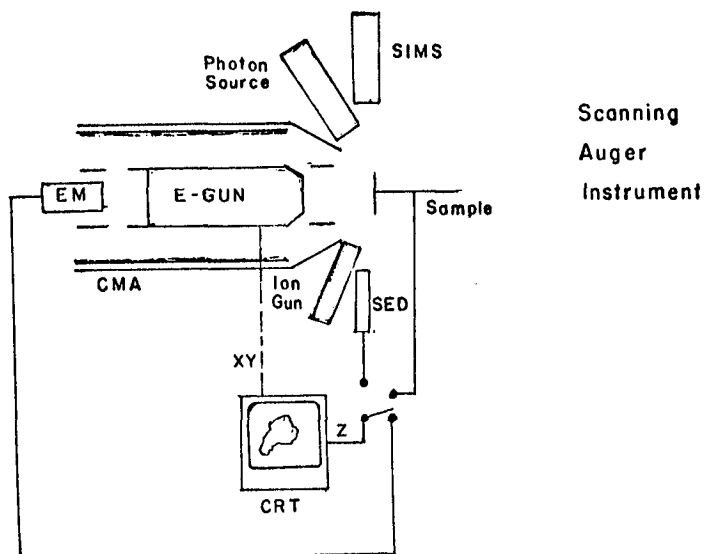
MOST ELEMENTS
CHEMICAL EFFECTS
SEMI-QUANTITATIVE
MINIMAL SAMPLE DAMAGE

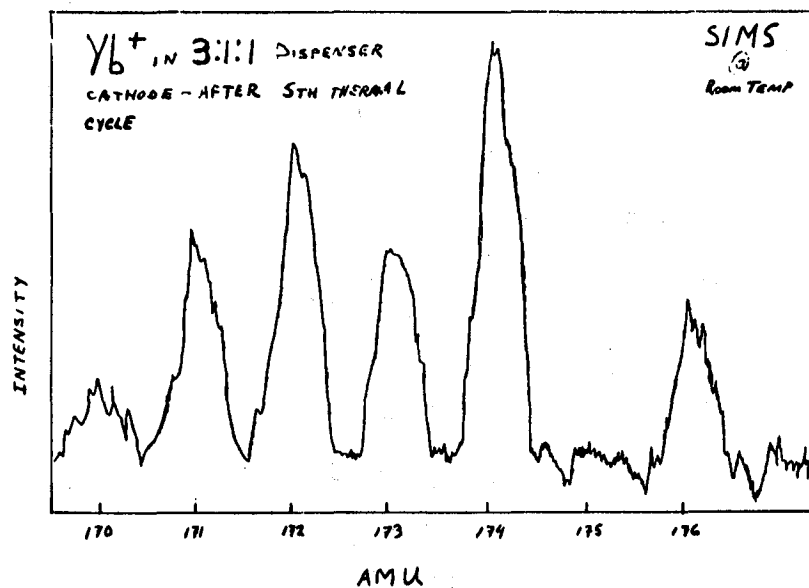
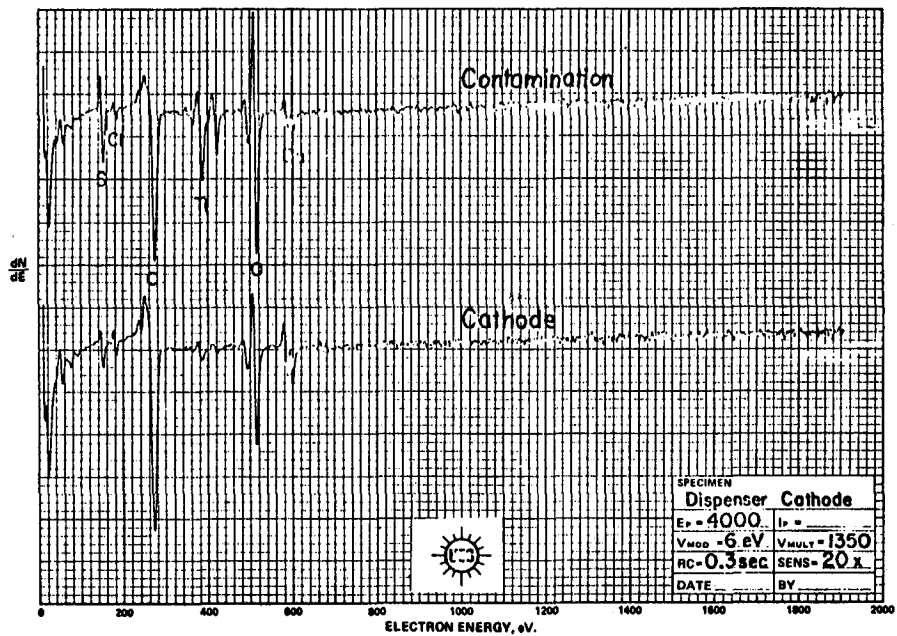
SLOW
NO ISOTOPE SEP.
H, He EXCLUDED
NO MAPPING, LARGE AREA

AES

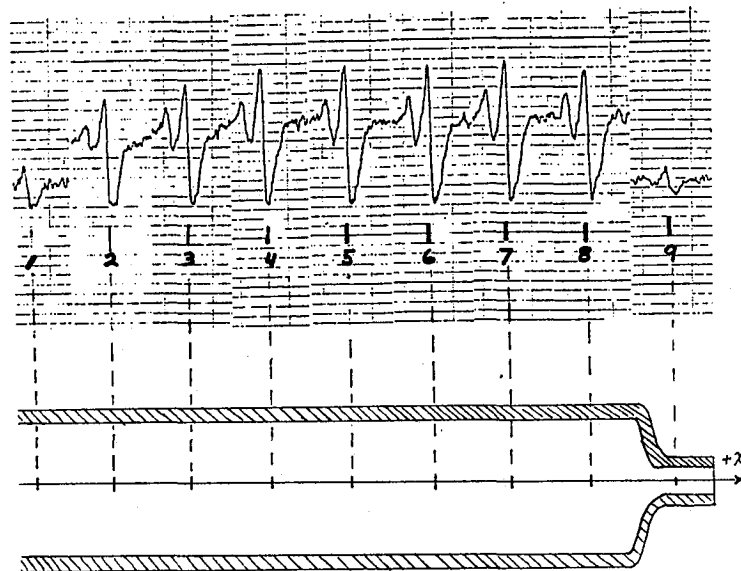
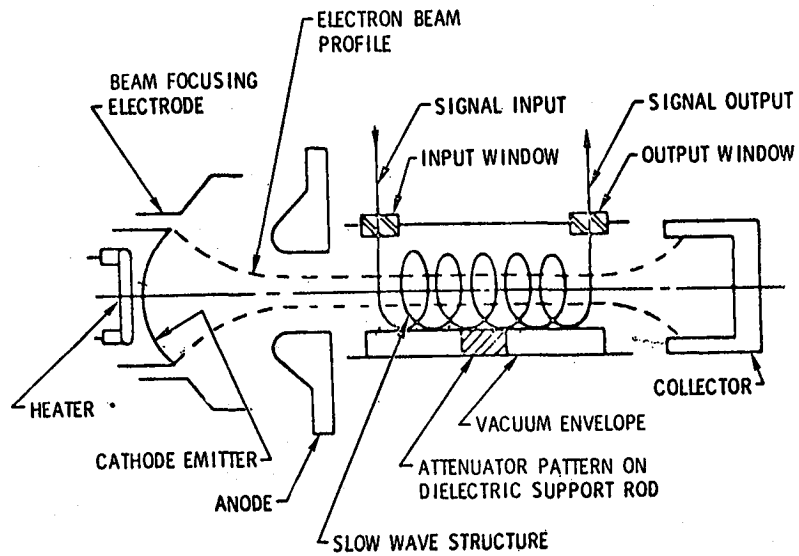
FAST
MAPPING
MOST ELEMENTS
CHEMICAL EFFECTS
SEMI-QUANTITATIVE
METALS, INSUL., SC
NOT CONSUMING

E-BEAM DAMAGE
SENSITIVITY > 0.1%
NO ISOTOPE SEPARATION
H, He EXCLUDED
PEAK OVERLAP





TWT Schematic



N_{KLL} Auger peak-to-peak height as a function of distance along collector of tube # S/N 201

Robert Longo, Hughes: "Retarded Field Measurements and Their Use for Reliability and Quality Control"

Retarded field measurements have been around for many years, but have been very difficult to apply because you are measuring reversed currents in the range of nanoamperes. We've applied computer control in an attempt to get a measure of cathode temperature in actual TWTs. It is important in the life expectancy, and there was a gap in our ability to measure temperatures.

We found it was very sensitive to the way the tube was built-- brazes, welds, heat shielding.

We're getting control you just can't get by hand, stepping the heater, stepping through a range of reversed field voltages, measuring 100 times at five heater power settings, and getting a calibration of heater power versus temperature.

The slope of the curves at the inflection point, closes approach to the Boltzmann plateau (on the voltage-temperature curve), after a lot of computation, leads to a temperature-power curve. (This is much over-simplified, partly because of problems with the tape. - Ed.)

The apparent geometry effect seems to be because some slower electrons are caught by the focus electrode and not counted. The retarded field temperature is higher than it should be. We are working to correct that.

The bi-modal distribution for production tubes is the result of a slight change in the gun and heater, not known by us when the measurements were made.

It take 1-2 hours to make these measurements. First we get a power-temperature curve with retarded field measurements, and then work backward to measure cathode work function. It often takes 20 minutes to get equilibrium (a stable work function). We're not really there, I'm not satisfied.

To summarize, we're using retarded field techniques to measure temperature and cathode quality in finished tubes, which was formerly very difficult to do. We're not completely there with retarded field either, but this technique shows variations from tube to tube. We get very repeatable measurements, repeatable within 2-5% on the same tube. With large perveance gridded tubes, the accuracy is very good.

Q: What effect do you get with poor tubes?

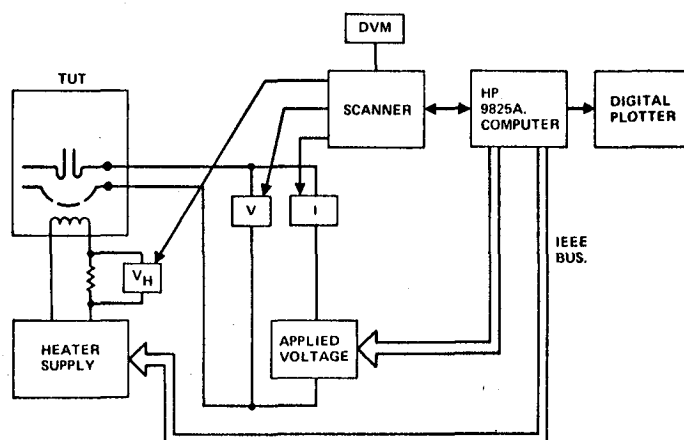
A: We have been able to show that tubes which were considered poor were not running hot enough. The retarded field does not depend on the properties of the cathode as long as the cathode work function is lower than the anode work function and there is sufficient current to measure.

- Q: But can you predict poor cathodes?
- A: We're just not there yet on work functions.
- Q: About last slide which showed work function of 1.98 ev.
- A: That's an average. The barium coverage depletes as a function of temperature.
- Q: But you can determine the temperature coefficient of the work function?
- A: Yes.
- Q: The value you get is dependent on the anode work function. You assume that is constant?
- A: Yes. The work function we get is not yet self-consistent. The temperature-power relationship can be used as quality control. We're not quite there on cathode work function.
- Q: Do you use thermocouples?
- A: They are usually used in lower temperature, oxide type tubes. We get large differences between thermocouple and retarded field measurements (because of "energy filtering").
- Q: Do we have a "unified field theory" where by means of various measurements we could evaluate the true state of health of the cathode when it goes into the spacecraft?
- A: We're not there yet. I think that's one of the things we need.
- Q: How did we get from cathode current, voltage gradient to temperature?
- A: (Short discussion of Boltzmann distribution.) The current in the retarded field region as the field is swept, is a sample of the thermal distribution. The slope of the current versus voltage is that exponent, or ev/Kt , so the slope is essentially $1/T$ in absolute scale.

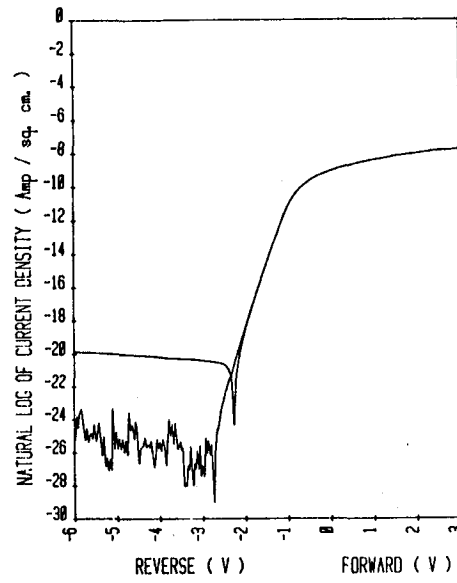
RETARDED FIELD MEASUREMENTS

- COMPUTER CONTROL MEASUREMENTS
 - GENERAL CHARACTERISTICS
- TEMPERATURE
 - REPEATABILITY
 - ABSOLUTE
- QUALITY AND RELIABILITY
 - SENSITIVITY TO CHANGES
- CATHODE QUALITY DETERMINATION
 - WORK FUNCTION

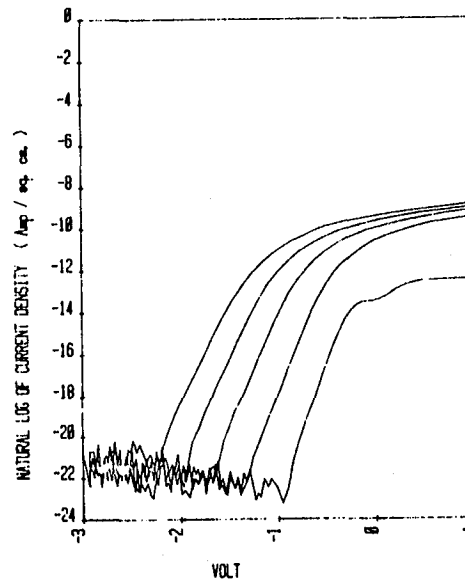
COMPUTER CONTROL MEASUREMENT - BLOCK DIAGRAM



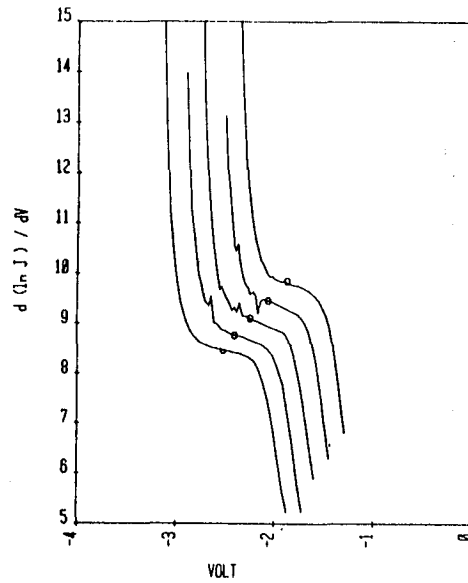
GENERAL RELATIONSHIPS OF VOLTAGE - CURRENT CHARACTERISTICS



RELATIONSHIPS OF VOLTAGE - CURRENT TO CHANGES IN HEATER POWER

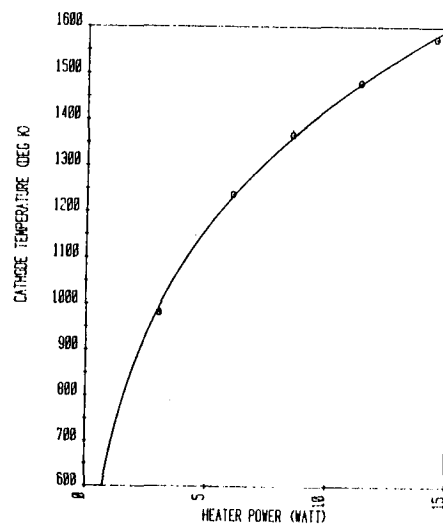


DERIVATIVE OF VOLTAGE - CURRENT CHARACTERISTICS

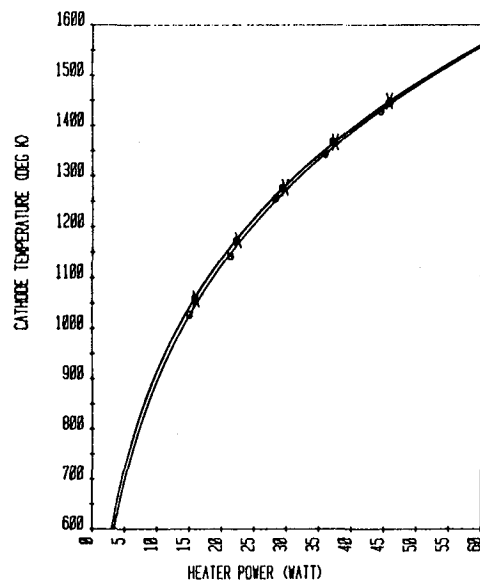


HEATER POWER VS. TEMPERATURE CURVE

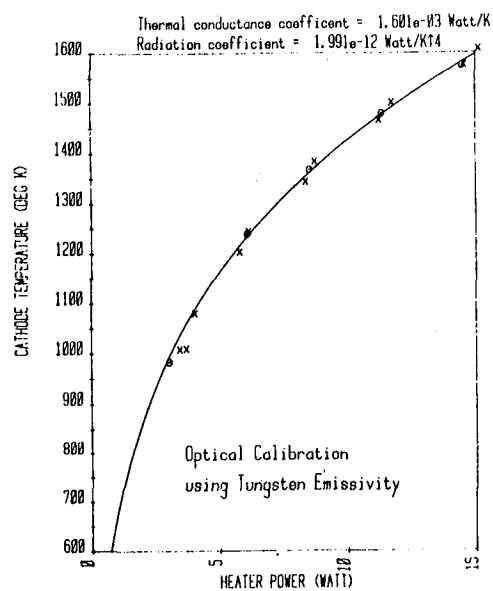
$$P = A (T - T_0) + B (T^4 - T_0^4)$$



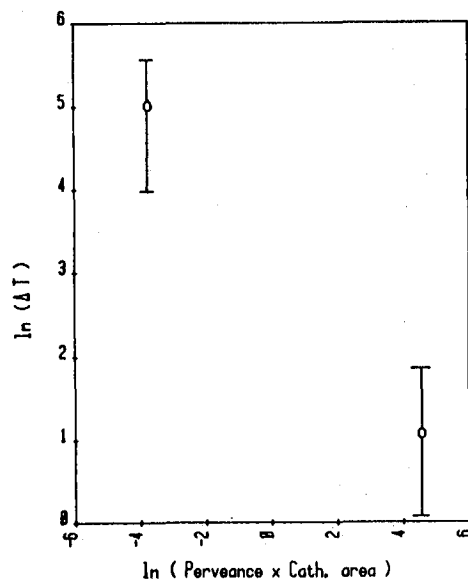
REPEATABILITY OF MEASUREMENT



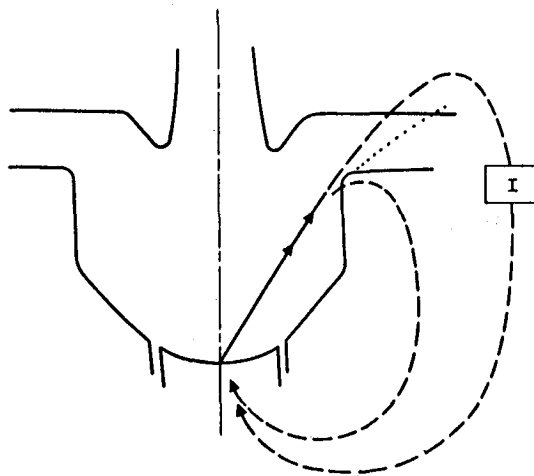
ABSOLUTE TEMPERATURE (CALIBRATION)



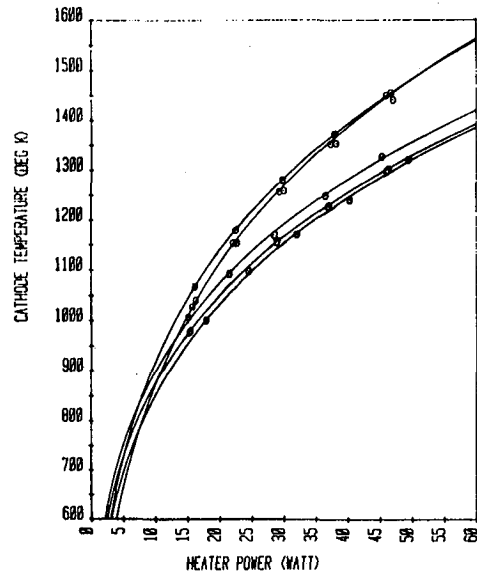
GEOMETRY EFFECTS ON TEMPERATURE



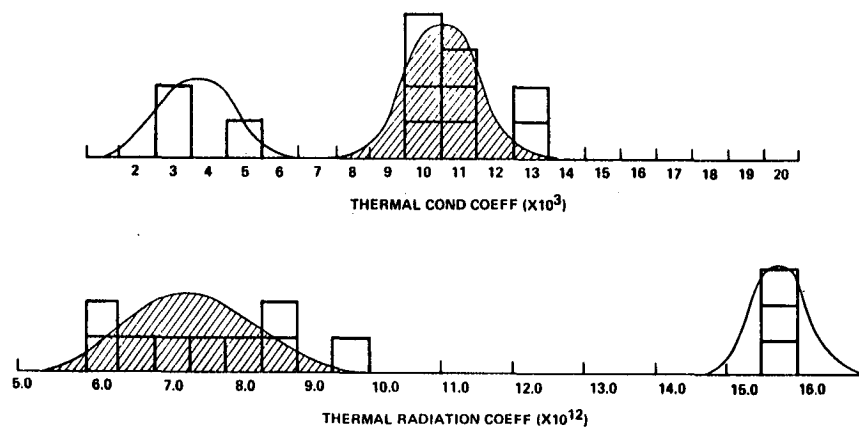
ENERGY FILTERING OF THERMAL DISTRIBUTION



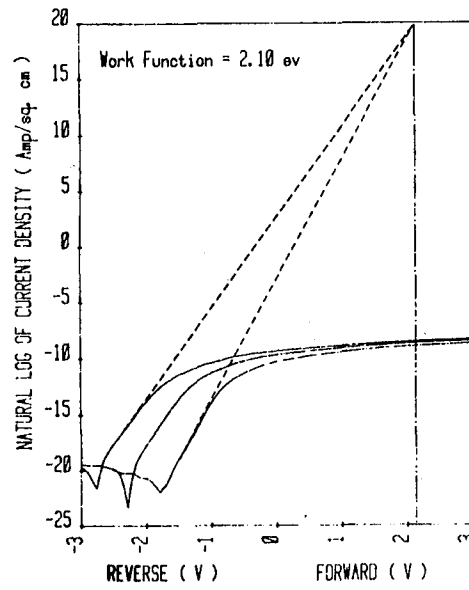
REPEATABILITY OF MEASUREMENTS WITHIN A PRODUCTION RUN



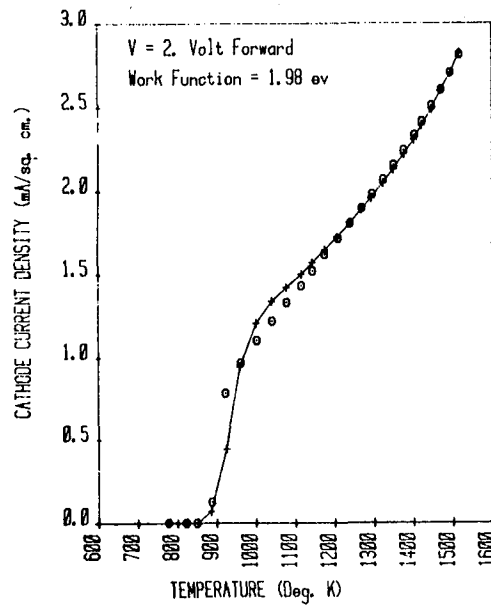
POPULATIONS OF PRODUCTION TWTS SHOWING CHANGES IN RADIATION SHIELDING



CATHODE QUALITY-WORK FUNCTION DETERMINATION



CATHODE QUALITY-WORK FUNCTION DETERMINATION



SUMMARY OF RETARDED FIELD TECHNIQUES

- **CATHODE TEMPERATURE MEASUREMENTS**
 - **MEASURABLE IN FINISHED TUBES**
 - **REPEATABLE AND ACCURATE**
 - **GEOMETRY DEPENDENT**
- **SENSITIVE TO VARIATIONS IN MANUFACTURING PARAMETERS**
- **CATHODE QUALITY CHARACTERIZATION**

Lou Dombro, Watkins-Johnson: "Update on Cathode Life Tests"

This program has been going on for about seven years now, sponsored by NASA-Lewis, Ralph Forman is the program manager.

The thermocouples proved to be ineffective; we rely on pyrometric measurements to measure temperature.

We monitored cathode current at a constant anode voltage, anode voltage at a constant cathode current, and cathode temperature and cathode temperature at a point where cathode emission had dropped to 80%. (The initial point is 2 A/cm²).

(Several separate plots are summarized in this graph, supplied by Ralph Forman.)

Q: About rising anode voltage--

A: (Dombro and Forman) The cathode current was kept constant, and as the cathode degraded, the anode voltage had to be increased. When we plot current at constant voltage, that is a reflection of that, the inverse. We also measured the temperature to get 80% of the space charge limited current. (When T_{80%} reaches the operating temperature, we considered that to be end of life.)

Q: The long term life testing is at constant current?

A: (Dombro) At constant temperature.

(Forman) We did not suspect that cathode current would degrade. The data from close-spaced diodes suggested that the current would stay constant until end of life, when it would drop off radically. We set it up to run at 2A/cm²; however, about 10,000 hours into the experiment we realized we were getting degradation. Hughes observed the same thing. However, since we had started that way, we ran at constant current and boosted the anode voltage. But we periodically measured the current at the original voltage as a measure of degradation. We also considered it a failure if, at the cathode temperature (1100°C), the anode voltage had to be raised more than 10% (i.e., it was a constant temperature, constant current life test except when data was taken.)

Q: Are there studies as to peak loading, as at the edges?

A: This is the average. There is a discussion of this in one of the reports. (Forman) We think these tests are very reliable; the cathodes seem to fail at about the same time. (Dombro) I think the tungsten cathodes were prematurely put into this program. They weren't ready.

Q: (Inaudible)

A: There were some deliberate changes in temperature, early, because that's part of the aging characteristic of the particular cathode. (Forman) There were some operator problems in measuring temperature at 12,000 hours point.

Q: In the matrix cathodes, the microstructure, little islands....have the failed cathodes been analyzed?

A: No. (Forman) We can do a surface analysis. We have failed cathodes and never-used cathodes, before and after, so we can look at them, but we haven't yet.

Q: Over the 70's the lifetime requirements have gone from 3 years to 10 years. It may be mid-80's before we understand the basic physics and chemistry of cathodes. What lifetime are we getting now, and is there anything we can do to maximize life before the next generation of tubes?

A: Basically, we should easily get 7-10 years of life...with oxide cathode tubes.

Q: In spite that, it looks like failures. What are we doing?

A: I'm not sure most of the failures are really wearout failures. (Some debate about this point and whether the models are valid.)

Q: About adequacy of government work, outlook.

A: (Sivo) What I'd like to do here is lay out some sort of consensus approach. We have a responsibility, and if we can identify what needs to be done, we will try to see it gets done. It bothers me that we have to ask, "What's the problem?" I need advice.

COMMENT: We've imperfectly understood the oxide cathode. We might learn more in the next 10 years than we have in the last 50.

COMMENT: (Alexovich) We were testing impregnated cathodes at 10 times the current density you get with oxide cathodes. I don't think the life test data should be compared.

Q: Are there any government agencies taking an in-depth look at oxide cathodes, or is it too late?

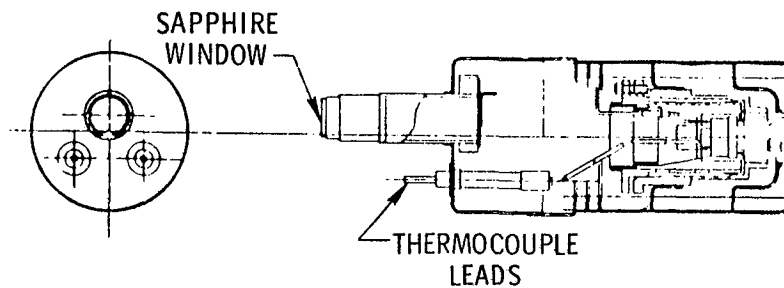
A: (Sivo) It can't be too late if we're going to keep using them.

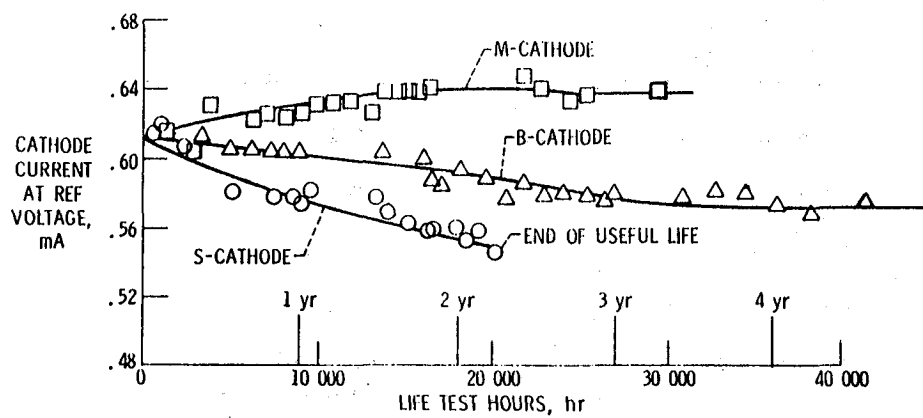
COMMENT: University of Dayton is looking at nickel-based cathodes, but a lot of that is applicable to oxide cathodes. The contract is from the Air Force Avionics Laboratory. Lt. Dave Corneille is project engineer of that contract.

COMMENT: Intelsat is sponsoring two study programs, one on oxides and one on matrix cathodes, which involve evaluating pulse measurement techniques. The work will be finished in the next year. I'm not sure how directly it will become available; I think the information will diffuse.

PARAMETERS FOR THE CATHODE LIFE TEST UNITS

Anode Voltage	Approx. 10,000 V
Cathode Current	0.620A
Gun Perveance	0.598 micropervs
Cathode Diameter	0.240 inches
Cathode Curvature Radius	0.315 inches
Cathode Half Angle (Θ)	22 degrees
Mean Cathode Loading	2.0A/cm ²
Max. Cathode Density/Min. Cathode Density	1.175
Minimum Beam Diameter	0.0293 inches
Beam Area Convergence Ratio	67.1
Brillouin Field	1745 gauss
Body (drift tube) voltage	Approx. 8 kV
Collector Voltage	Approx. 4 kV
Focusing type	Confined flow 86 % cathodes Flux immersion
Maximum Magnetic field	Approx. 3,000 gauss
Collector	Liquid Cooled





SESSION III - POWER SUPPLIES AND INTERFACES

Clifford Siegert, NASA-LeRC: "Power Supplies"

After you have a breadboard, the next phase is to package the power supply for space operation. I'd like to talk about a power supply built for NASA by TRW, and 11 kV supply which has been operational in space for more than three years--the design guidelines and testing done at the component level.

The designer divides his power processor into a low voltage and a high voltage section, voltage partitioning. Likely he'll put a metal wall between them, but you still have signals between the sections. In this supply, we designed it so all grounds were isolated, to provide a means to predict what currents we would have when there were transients and arcing. When capacitors discharge, there can be currents of hundreds of amps. It is necessary to take steps to protect the low voltage section from current surges.

Electric fields. Design guidelines that were used: solid dielectric, DC, below 50V per mil; AC stress, 10V per mil; surface creepage, 8V per mil; air (sea level) or vacuum (10^{-5} Torr) gaps, 20V per mil. Venting, greater than 2 cm² per 100 cm³ volume. Allow for screens, rf traps, etc.--count only the holes in the screens. Don't forget interior volumes, right down to cap nut plates. Unless you make certain that all volumes are vented, you can operate up to a month in a vacuum, and when you get up to temperature, zap.

Round off all edges, on dielectrics as well as metal. Use anti-corona spheres. Void-free encapsulation is important. Remove excess RTV from bolts to keep vent paths open. Use shrink tubing in strips for hold downs, to avoid voids. (Discussion of several non-reproducible photographs.) There is a NASA TM X-73432 on testing, including non-destructive ultrasonic examination to check for board density differences.

We selected 5 picocoulombs, which was the sensitivity of the instrument, as a standard for corona testing. We did the testing called out in MIL-T-27, induced voltage in the dielectric, which must be done in a vacuum at temperature. Then we repeated the corona tests to detect internal degradation (from the high voltage stress). Be careful to bake out; the components will see only 65°C, applied externally, so they won't be damaged, but you have to cool it down before you turn it on.

The manufacturer has to understand what the designer had in mind (vent paths, etc.), and what tests will be applied. The entire program has to be thought through before you start phase I, so that you prevent problems instead of having to cure them.

Q: At what voltage potential is it essential to use anti-corona spheres?

A: We used them throughout. Even at 2 or 3 kV, you should pay attention to sharp edges and points.

Q: You showed us a transformer. Do you maintain surface creep criterion after it's potted?

A: We tried to keep open construction, except the transformers and inductors had to be potted. The surface creepage I'm talking about is when you have two conductors separated by a dielectric; it doesn't apply to insulated wires.

Q: Where you pot insulated components on a board, do you use assume bonding?

A: No, use the creepage criterion between the cooling and the board. The interface is just not homogenous enough. Sometimes you have two conductors with a vacuum gap. Then you try to improve it by putting insulation between them, and it's worse. Insulators can get charged up, and you have cut down the spacing.

Q: How was the CTS operation in space?

A: In space we have had no failures. We had current sensors on board that were good for 15 milliamps to detect leakage currents. We have checked that repeatedly. There has been no change (from ground test).

COMMENT: With the cathode heater off, the voltage went up to 13 kV, but we saw no evidence of leakage or arcs. We did expose the package, power supply and tube. It was exposed to hard vacuum for three weeks, to allow it to vent, before we turned it on.

Q: Did TRW use some margin beyond your design requirements?

A: No. They knew they were going to run it at $2\frac{1}{2}$ times operational voltage. The only place we didn't follow our own criteria was the high voltage transformer, it runs 55 Volts per mil.

SOME PROBLEMS AND SOLUTIONS IN PACKAGING
HIGH VOLTAGE SUPPLIES FOR SPACE

DESIGN GUIDE LINES

PHYSICAL LAYOUT
ELECTRIC FIELDS
VENTING

FABRICATION

DIELECTRIC MATERIALS
PHYSICAL CONFIGURATION

TESTING

ULTRASONIC SCANNING
CORONA TESTING
ELECTRICAL TESTING

DESIGN GUIDE LINES

PHYSICAL LAYOUT

VOLTAGE PARTITIONING (SEPARATE HIGH AND LOW VOLTAGE COMPARTMENTS)
ISOLATED GROUNDS (PROVIDE KNOWN CURRENT PATH FOR TRANSIENTS)
VOLTAGE SUPPRESSION (SIGNAL FROM HIGH VOLTAGE TO LOW VOLTAGE CIRCUITS)

ELECTRIC FIELDS

SOLID DIELECTRIC

DC STRESS	50 VOLTS/MIL
AC STRESS	10 VOLTS/MIL
SURFACE CREEPAGE	8 VOLTS/MIL
AIR OR VACUUM GAP	20 VOLTS/MIL

VENTING

$>2\text{cm}^2$ PER 1000cc OF ENCLOSED VOLUME (SCREENS AND RF TRAPS REDUCE VENT SIZE)
CAPPED NUT PLATES
DIELECTRIC SPACERS
POLYOLEFIN SHRINKABLE TUBING
HIGH VOLTAGE CONNECTORS

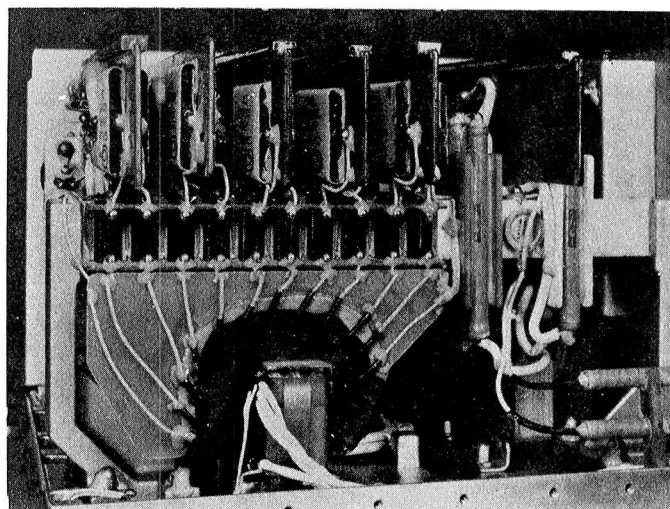
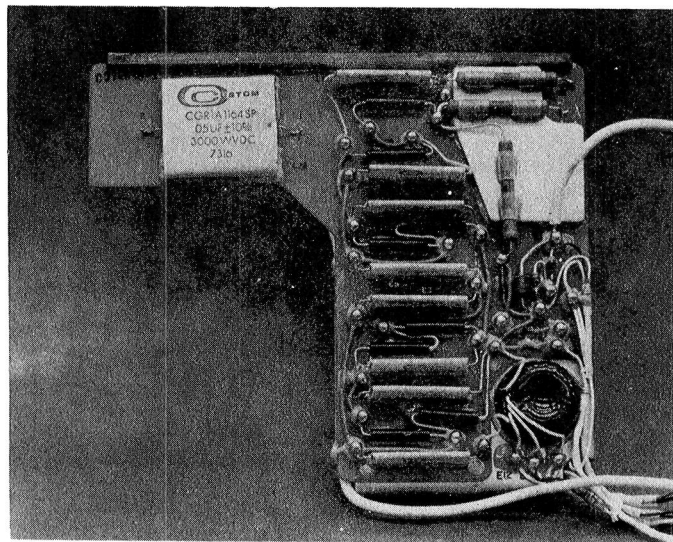
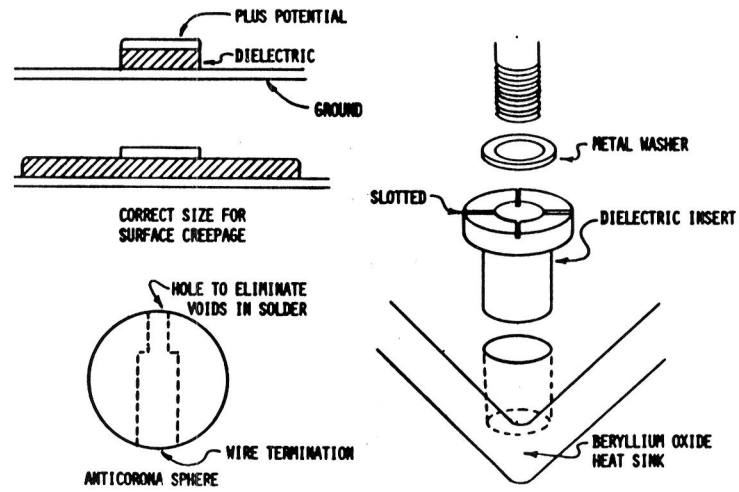
FABRICATION

DIELECTRIC MATERIALS

GLASS EPOXY
POLYIMIDE
BERYLLIUM OXIDE
FILLED EPOXY (TRICAST, LEFKOWELD)
LOW OUTGASSING SILICONE RUBBER RTV 566

PHYSICAL CONFIGURATIONS

ROUND OFF ALL SHARP EDGES
ANTICORONA SPHERE
VOID FREE ENCAPSULATION



TESTING

ULTRASONIC SCANNING OF GLASS EPOXY BOARDS (NASA TN X-73432)

CORONA TESTING

TRANSFORMERS
COMPONENT CONFIGURATION ON BOARDS
<5 PICOCOULOMB

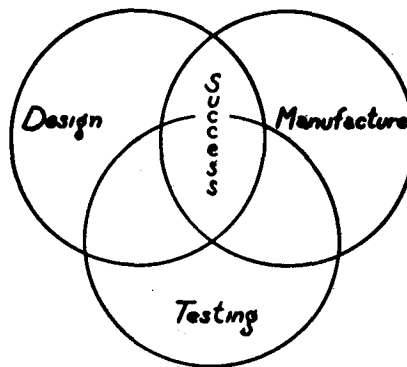
ELECTRIC TESTING

INDUCED VOLTAGE (TWICE RATED VOLTAGE)
DIELECTRICAL WITHSTANDING (2.5 TIMES RATED AC AND DC)
IMPORTANT TO PERFORM IN VACUUM AT TEMPERATURE

THERMAL TESTING

MINIMUM OF 10 TEMPERATURE CYCLES AT COMPONENT LEVEL
MINIMUM OF 3 TEMPERATURE CYCLES AT BOX LEVEL

INITIAL THERMAL-VACUUM TEST PRECEDED BY BAKEOUT OF 65°C FOR 72 HOURS



Bill Harrigill, Ira Myers, NASA-Lewis: "Do We Want Transformerless Power Supplies?"

(Harrigill) The transformerless capacitance diode voltage multiplier (CDVM) is a NASA development. The energy is transferred electrostatically rather than electromagnetically. It operates at high frequencies internally, at present 50-100 kHz, so the components can be smaller and lighter.

The switches, the power transistors, make an AC square wave which charges all the capacitors of the multiplier to the peak of the AC wave, which is the sum of the DC inputs. The voltage across the load is the sum of the voltage across all of the stages in series. The output voltage is the input times the number of stages, and the current the inverse. The input current is essentially a sine wave, and the transistors switch when the current is zero, which reduces the losses in the switches--very important. The two DC input voltages do not have to be equal; you can regulate by regulating one of them.

Another feature is that you can tap off at each stage of capacitance to get various voltages, which could be nice for getting multiple stages of collector depression for a TWT. One stage is two diodes and two capacitors. Each stage is exactly alike, which lends itself to standardization and modularization. If you want more voltage, just add more stages. Your testing can be done at low voltage, a stage at a time.

There are many types which have evolved from the basic circuit.

There are different types that can evolve: two transistor chopper, full wave bridge rectifier, single input or double input, two-phase, multi-phase--any number of phases you want. You can use partial power regulation, or you can isolate the input from the output by using a flying capacitor isolator. You can use single or multiple bias supplies, so you can tap off with supplies biased above reference or ground.

History--Before 1972, most engineers had heard of a voltage multiplier, but the wattages were extremely small. We brought it up in '75 to 100 Watts with good efficiency. We have a regulated system. In '77 we took it up to 10 kV at 100 watts, which, without the transformer is considerably lighter with less. Now we're looking to about a kilowatt at 10,000 or 11,000 volts.

There is a wide range of output wattage with a small change in efficiency. The weight is fairly low.

We don't know the limit on higher and higher frequencies, but it gets smaller and lighter as the frequency goes up. Of course at higher voltages, the weight goes up because you need more stages.

(Meyers) There has been a progression. Cliff Siegert talked about reality, something which has been flown. On CTS, the power supply is substantially larger than the tube it drives. I'd like to look into the future, with the CDVM. Our Lewis Research Center applications so far have been pointed toward the ion thruster, a kilovolt or two, different than the TWT application. We are also looking toward higher power in space, on the order of 200 kilowatts with distribution voltages on the order of 1000 volts. These are utility kind of things. TWTs are a future direction, but we haven't done that yet.

We're rather early on our learning curve. Already our weights are strongly competitive with the current transformer type power supply. We've only investigated two or three of the potential types. We're looking at higher frequencies, as newer components become available, like power MOSFETs which might run at 200 or 300 kilohertz or higher. Lightweight capacitors. We predict a promising future for the CDVM.

One of the things that's interesting is the possibility of driving multiple loads, tapped to various points on the drain.

It can be spread out, modularized, put in a corner or spread out on a plate. There are no big lumps; you can do almost anything with it. You can't make a good transformer long and skinny, whereas you can a voltage multiplier.

Possible smaller volume should be considered. You could mount the voltage multiplier directly on the tube and replace the two as a unit; probably difficult with a transformer. The distributed heat load may be an advantage. I show 90% efficiency. We showed you a converter with 96.5% earlier. There's a trade-off with size and weight, as with most things.

Q: How does regulation compare with the conventional transformer?

A: You can make it anything you want. You can use a buck-boost circuit on one of the inputs with a feedback circuit. If you want 1/10% you can have 1/10%. Everyone knows you can't regulate voltage multipliers, but that's not true. We can; we've got a patent on it.

Q: What happens if a diode or capacitor fails?

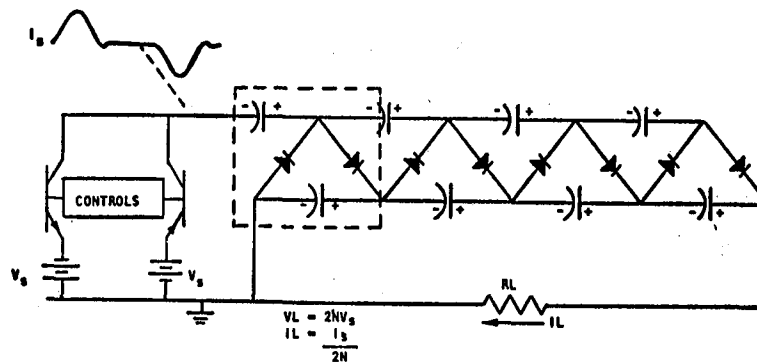
A: You can use the multi-phase approach. There are alternate paths through the module so you might have some degradation but not a complete failure.

Q: About filtering and millivolt regulation specification.

A: It may not require extra filtering, but you can add extra filtering as you would to any power supply. It's fairly easy to attain, because the ripple frequency is high, perhaps 100 kHz. To filter against the opposite, feeding signal back onto the power supply, there are two things to be considered. A noise signal is probably at 70 or 100 kHz, and the input filter can probably be smaller than the conventional system. The tube itself having some kind of transient--it might be the same as for a conventional system. There might not be any advantage there.

WHAT IS THIS NEW POWER SUPPLY TECHNOLOGY

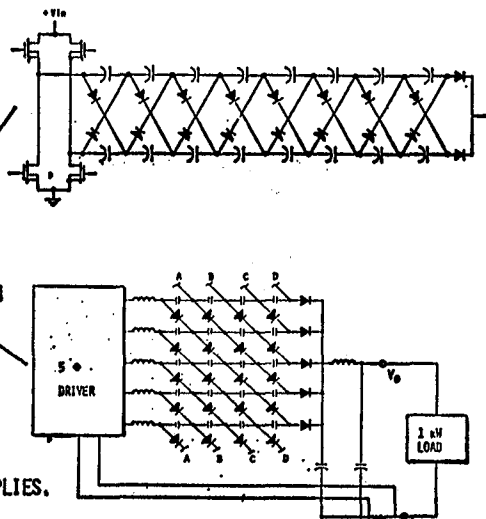
- USES CAPACITANCES AND DIODES INSTEAD OF TRANSFORMERS TO CHANGE LOW VOLTAGE TO HIGH VOLTAGE ELECTRICAL POWER.
- OPERATES AT HIGH FREQUENCY INTERNALLY, WHICH ALLOWS SMALL COMPONENTS AND THEREFORE LOW WEIGHTS.
- NAME - "CAPACITOR DIODE VOLTAGE MULTIPLIER".



TRANSFORMERLESS CAPACITOR DIODE VOLTAGE MULTIPLIER DC-DC POWER CONVERTER

CDVM CIRCUIT TYPES

- TWO TRANSISTOR CHOPPER
- TRANSISTOR BRIDGE CHOPPER
- SINGLE INPUT VOLTAGE
- DOUBLE INPUT VOLTAGE
- TWO PHASE VOLTAGE INPUT, CDVM
- MULTI-PHASE VOLTAGE INPUT, CDVM
- MORE COMPLEX SYSTEMS
- FLYING CAPACITOR ISOLATOR
- PARTIAL POWER REGULATION
- SINGLE AND MULTIPLE BIASED SUPPLIES.

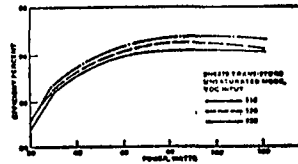


NASA-LEWIS CDVM DEVELOPMENT

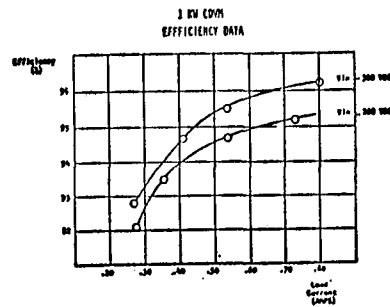
- 1972 - BREADBOARD - 7-WATT - 1000V
- 1973 - BREADBOARD - 65-WATT - 1000V
- 1974 - 100-WATT CONVERTER - 1000V
- 1975 - HIGH EFFICIENCY 100-WATT CONVERTER - 1000V
- 1976 - REGULATION METHOD DEVELOPMENT (SYSTEMS IMPLEMENTATION BY HUGHES AIRCRAFT)
(PATENTED BY NASA-LEWIS)
- 1977 - LONG CHAIN - HIGH VOLTAGE (10 kV) CONVERTER - 100 WATTS
- 1978 - 1500 WATT, 1200V CONVERTER

CONTRACT ACTIVITIES/HUGHES AIRCRAFT

- 100-WATT CONVERTER
 - SHORT CIRCUIT PROTECTION
 - CLOSED LOOP REGULATION
 - TWO-PHASE OPERATION
 - EFFICIENCY - 91%
 - COMPONENT WEIGHT, 1 KGM/KW



- 1.2-KW CONVERTER
 - SHORT CIRCUIT PROTECTION
 - UNREGULATED
 - FIVE PHASE OPERATION
 - EFFICIENCY 0 96.5%
 - COMPONENT WEIGHT, 0.55 KGM/KW



SUMMARY - CHARACTERISTICS OF CDVM POWER SYSTEMS

- VERY LIGHT WEIGHT
- MEDIUM TO HIGH FREQUENCY
- VOLTAGE CONVERSION DONE BY DIODES AND CAPACITORS INSTEAD OF TRANSFORMERS
- ACTS AS ITS OWN FILTER. OFTEN NO OUTPUT FILTER IS NEEDED.
- RELIABILITY EXPECTED TO BE COMPARABLE WITH MORE CONVENTIONAL POWER SYSTEMS
- WEIGHT INCREASES AND EFFICIENCY DECREASES FOR HIGHER VOLTAGE RATIOS.

LERC FUTURE TECHNICAL DIRECTIONS

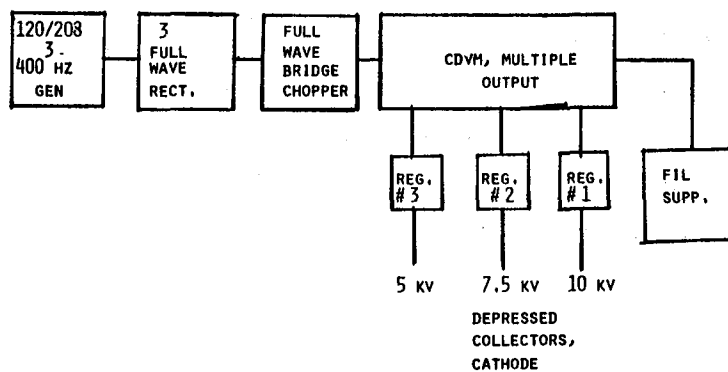
● APPLICATIONS

- ION THRUSTER
- HIGHER POWER FOR SPACE SYSTEMS
- TWT

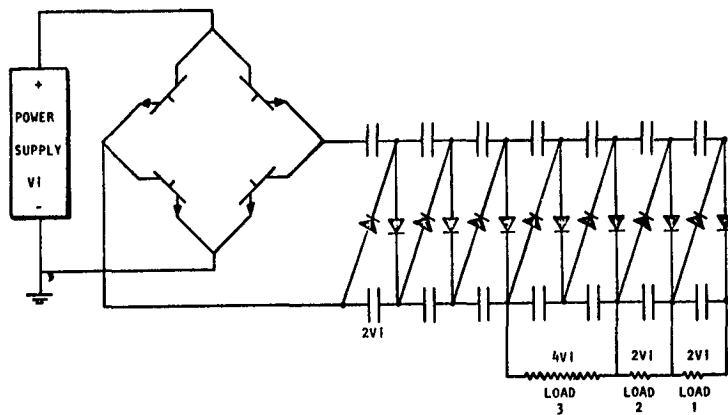
● NEW TECHNOLOGY

- NEW CIRCUIT TECHNIQUES
- HIGHER FREQUENCY CIRCUITS
- BETTER COMPONENTS

BLOCK DIAGRAM FOR DEPRESSED COLLECTOR TWT CDVM POWER SUPPLY



ONE POSSIBLE CONFIGURATION OF A
CDVM WITH MULTIPLE LOADS, TWT MDC's



SUMMARY - CHARACTERISTICS OF CDVM POWER SYSTEMS

- VERY LIGHT WEIGHT
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PRELIMINARY CONCLUSIONS

CDVM LENDS ITSELF TO AN INTEGRATED MODULAR DESIGN

- SMALLER VOLUME
- UNIT REPLACEABILITY
- DISTRIBUTED HEAT LOAD

WEIGHT REDUCED ABOUT 40% (BASED ON SPACE APPLICATIONS)

EFFICIENCY ABOUT 90% (ALSO BASED ON SPACE APPLICATIONS EXPERIENCE)

ELIMINATION OF TRANSFORMER

EFF VS WT TRADES CAN BE MADE TO OPTIMIZE EITHER PARAMETER

RECURRING COST - NOT INVESTIGATED, BUT SHOULD BE LESS THAN CONVENTIONAL SUPPLY.

N. J. Stevens, NASA-LeRC, "Techniques for Assessing and Controlling
Spacecraft Charging Effects"

Problems arise from a geomagnetic substorm, which is essentially a plasma cloud. The solar wind interacts with the earth's magnetic field and forms a bow shock wave about 10 earth radii away on the sunward side. Particles cross the shock wave, are trapped in magnetic fields, are moved out to about the orbit of the moon, then brought back and accelerated by some mechanism, still unknown, but thought to be an oscillation of the earth's magnetic and electric fields. The particles form a plasma cloud of kilovolt electrons and high energy protons which can interact with geostationary satellites. This phenomenon is called a substorm, because it is localized, usually in the higher latitudes. It is thought to be the cause of the aurora borealis.

The spacecraft will come into equilibrium such that the net current is zero. In quiet environments, the particle fluxes are on the order of picoamps or tens of picoamps per square centimeter. These fluxes are balanced by photo emission and secondary emission leakage. The spacecraft could be about 20 volts positive in the sunlit areas and 20 volts negative in the shaded areas. When it encounters the plasma cloud of the substorm, where fluxes are about a nanoamp per square centimeter, the equilibrium potential in the sunlit areas can be up to 2000 volts, and the shaded areas can be charged to kilovolts. The ATS-6 has been charged to about 2000 volts negative in sunlight, the spacecraft ground relative to the plasma. In eclipse, the ATS-6 has reached 19,000 volts negative.

If you get differential charging, discharging can occur. It can put out a pulse which can cause anomalous switching on board. The anomalies are plotted and show a maximum in the midnight to dawn quadrant. Because of the use of low-level logic, it doesn't take much of a pulse to cause switching problems, as shown on the slide, "Spacecraft Charging Investigation."

In 1976, the Air Force and NASA got together to work on descriptions of the environment, materials for spacecraft, ground based simulations, and a computer model for predictions, called NASCAP, for NASA Charging Analyzer Program. The Air Force has a SCATHA spacecraft, Spacecraft Charging at The High Altitudes, which has monitoring instruments and experiments. It was launched in January 1979 and is functioning very well. The output of this joint program is a design guidelines document and a test standard.

The substorm characteristics are put into the NASCAP program, with electron temperatures peaking at about 12 KeV. The proton temperature is assumed to be twice the electron temperature, which agrees well with measurements. The modeling approximates with steps of 30 minutes each. I want to talk about the high density case, where particle densities peak at five particles per cubic centimeter, which is still lower than what has been measured in space.

The model assumes a stabilized spacecraft as shown, with sunlight about 30° incident to the solar arrays, a June condition. The code allows discharges to occur with breakdown at edges of insulators, when the electric field gets to be 1.5×10^5 volts per centimeter.

The curves show a shaded Teflon region with, at worst, discharges about every 4 minutes. The code gives the field distribution around the spacecraft.

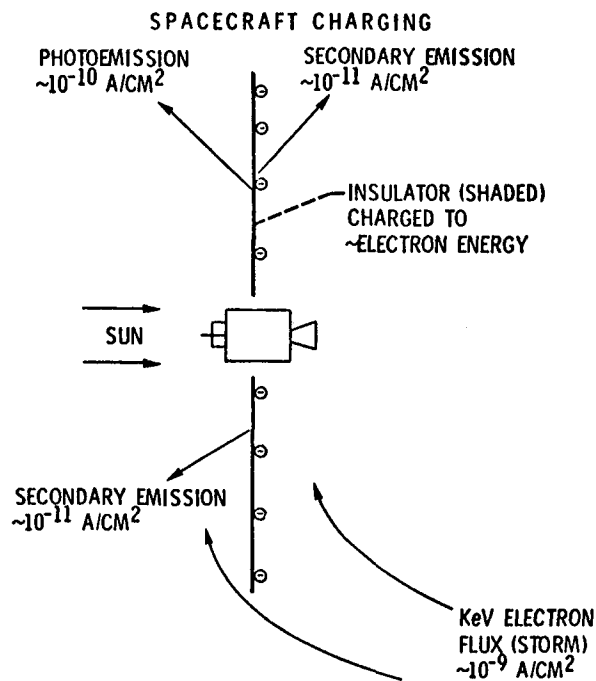
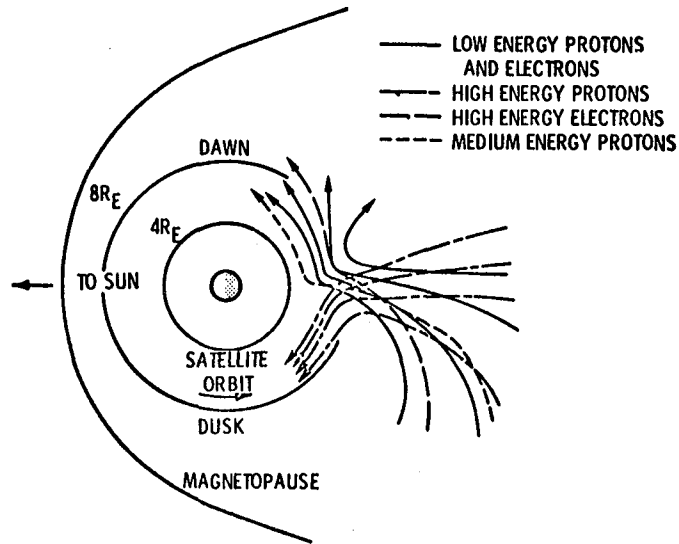
To control these effects, you can use passive techniques. You can relax the resistivities of the insulators so the leakage currents increase. I've modeled the spacecraft with the Kapton painted to lower the resistivity to 10^9 ohm-centimeters, down from about 10^{15} . It still charges and discharges, but it is more benign. The fields were relaxed, as desired, behind the solar arrays, but other shaded areas have to be worked over, too. One has to use the model to verify the fixes.

There are active controls, using filtering. It was done successfully on CTS, filtering all lines to reject any noise on the order of one to ten microseconds. DSCS II had a whole set of anomalies. The Air Force bought six more with added filtering. Four have been flown so far, with rejection of anything of a millisecond or less. The information I have is that the systems which have been filtered have no anomalies. Those systems which were not filtered, because they were non-sensitive, still have anomalies, noise on the line.

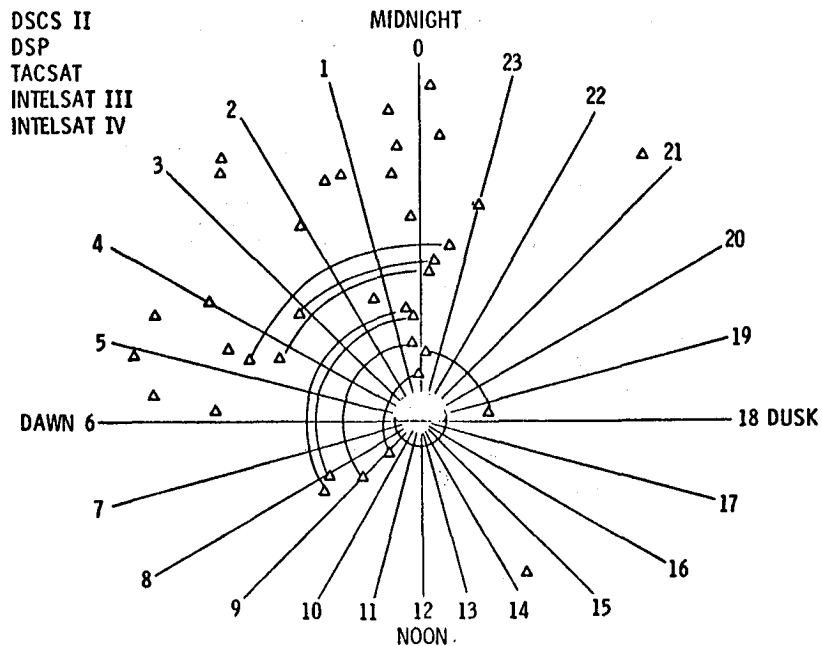
The spacecraft charging investigation has developed some frequency specs; noise with a rise time of up to 10 nanoseconds, a duration of about 10 microseconds, a frequency content up to 100 megahertz, and amplitudes up to 500 amps. This is the spectrum to filter against. Grounding of all the spacecraft materials is a good thing to do. This approach should be tested. The Voyager was tested about 9 months before launch, and the last 6 months was a frantic correction of what they found. The JPL people said it was worth the effort.

EDITOR'S NOTE: There was not time for questions.

SCHEMATIC VIEW ON THE GEOMAGNETIC EQUATORIAL PLANE
OF ELECTRON AND PROTON INJECTION EVENTS DURING
GROWTH PHASE OF A SUBSTORM



OCORRANCE OF SATELLITE ANOMALIES IN LOCAL TIME



SPACECRAFT CHARGING INVESTIGATION

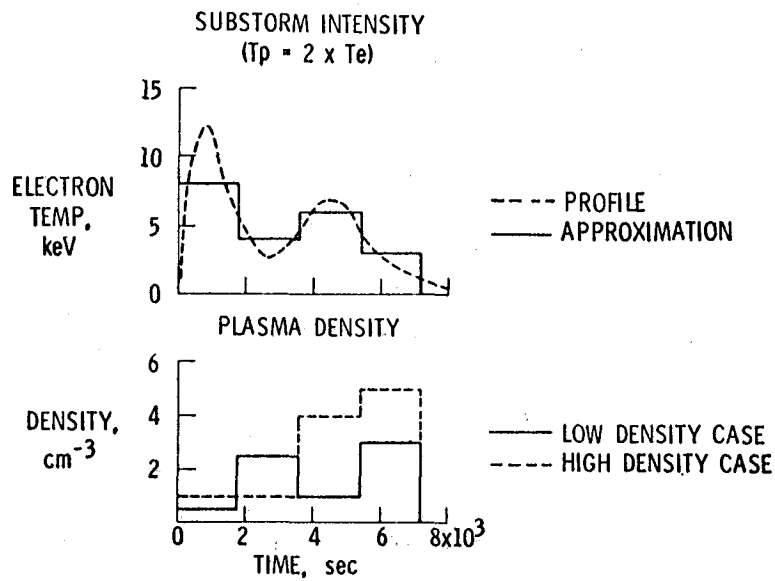
● DEFINITION

SPACECRAFT SURFACES CHARGED BY SPACE ENVIRONMENT

● HAZARD

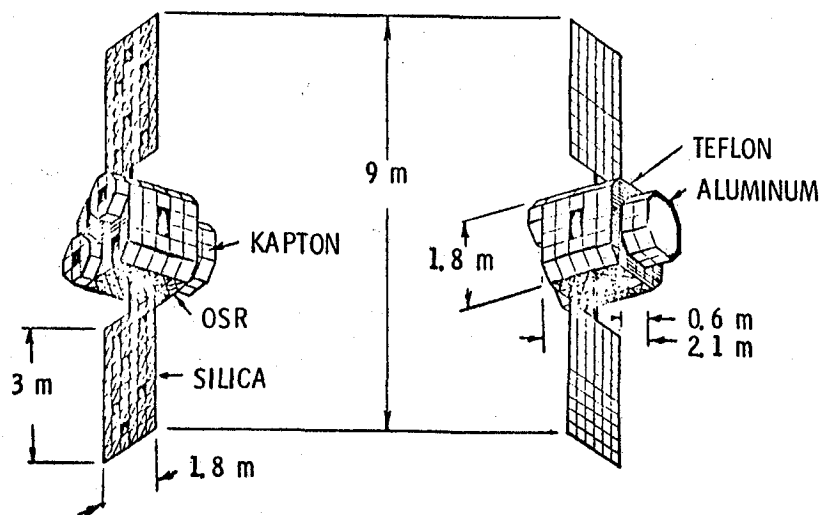
- DISCHARGES
 - DIFFERENTIAL CHARGING
 - EMI NOISE
 - ELECTRONIC SWITCHING ANOMALIES
 - THERMAL CONTROL COATING DEGRADATION
- INCREASED CONTAMINATION
- SCIENCE MEASUREMENT IMPACT

TRANSIENT SUBSTORM CHARACTERISTICS



CS-79-2838

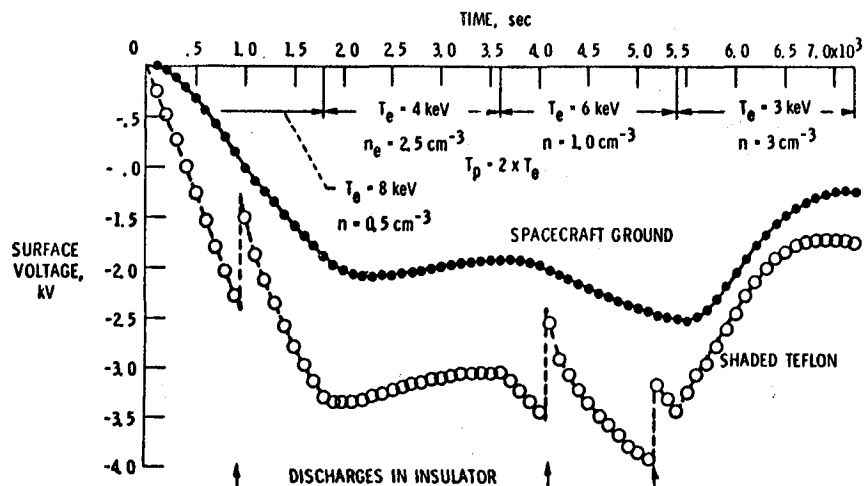
TYPICAL GEOSYNCHRONOUS COMMUNICATIONS SATELLITE



CS-79-2834

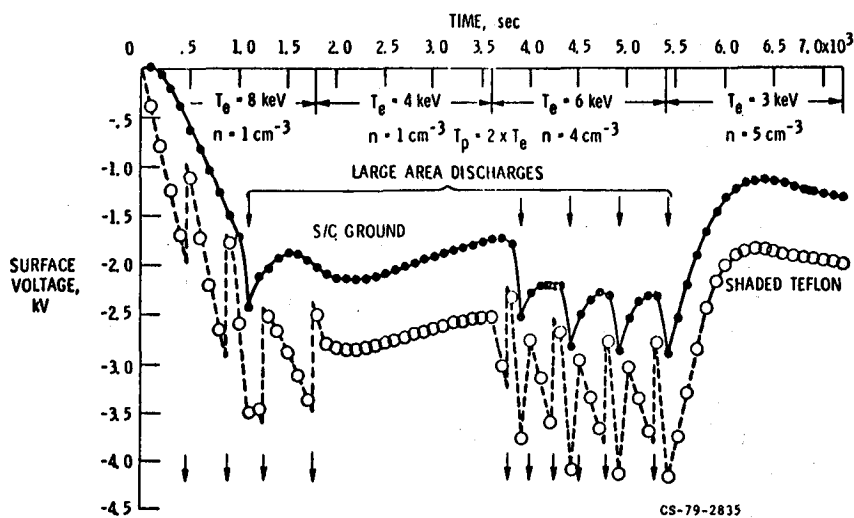
SATELLITE RESPONSE TO TRANSIENT SUBSTORM

SPACECRAFT BODY RESPONSE - LOW DENSITY CASE



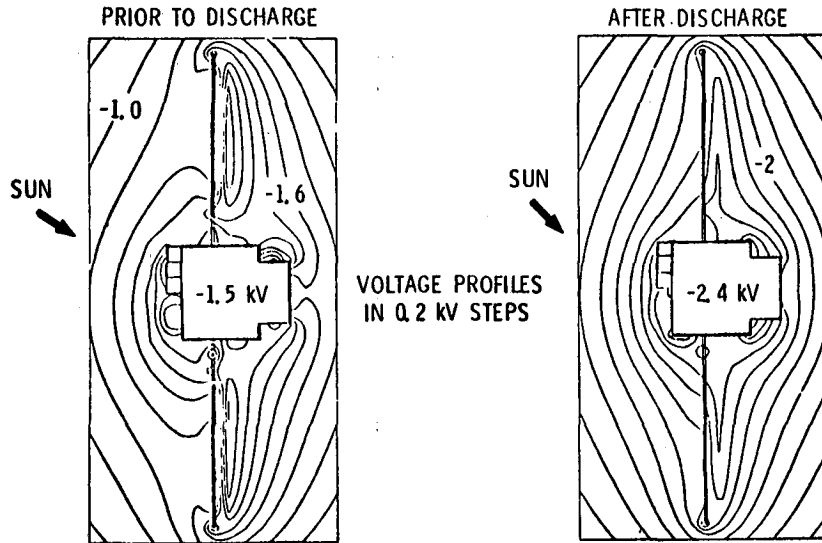
SATELLITE RESPONSE TO TRANSIENT SUBSTORM

SPACECRAFT BODY RESPONSE - HIGH DENSITY CASE



VOLTAGE PROFILES AROUND SATELLITE

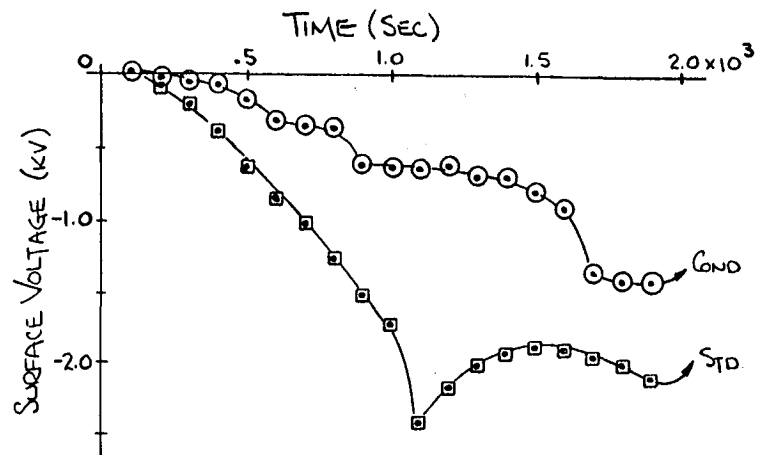
LARGE AREA DISCHARGE



CS-79-2836

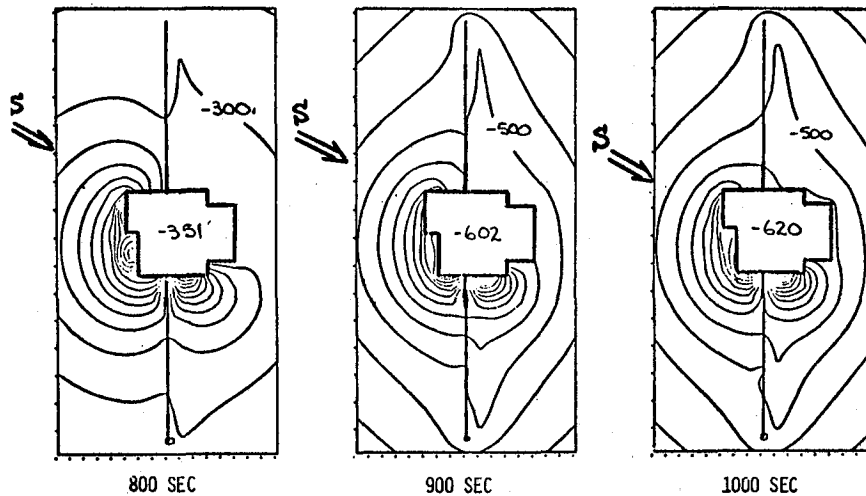
EFFECT OF QUASI-CONDUCTIVE INSULATORS

$(T_E = 8 \text{ KeV})$



EFFECT OF QUASI-CONDUCTIVE INSULATORS

(EQUIPOTENTIAL LINES 100V)



SPACECRAFT CHARGING EFFECTS

CONTROLLING EFFECTS

- ELECTRONIC CONTROLS
 - FILTERING
 - NOISE FILTERS
 - CTS 1-10, MICROSECOND
 - DSCS-II REPLACEMENTS, MILLESECOND
 - FREQUENCY SPECIFICATION (PROVISIONAL)
 - GROUNDING
- TESTING
 - DEMONSTRATE IMMUNITY TO UPSET
 - VOYAGER
 - SCATHA
 - COMPONENT TESTING
 - CTS
 - DSCS II
 - AF STANDARD

SPACECRAFT CHARGING INVESTIGATION

DESIGN GUIDELINES MONOGRAPH

(IN PREPARATION)

- SUBSTORM ENVIRONMENT
- ANALYSIS TECHNIQUE
 - MODELING
 - CRITERIA
- SATELLITE DESIGN
 - GUIDELINES
 - TESTING
 - MONITORS
- SYSTEM DESIGN
 - GUIDELINES

SPACECRAFT CHARGING EFFECTS

SUMMARY

- TECHNIQUES EXIST FOR EVALUATING SPACECRAFT CHARGING EFFECTS
 - PAST EXPERIENCES
 - GROUND TESTING
 - ANALYSIS
- CONTROL TECHNIQUES AVAILABLE
 - PASSIVE
 - o TRADE-OFF THERMAL VS. ELECTROSTATIC
 - ELECTRONIC
 - o FILTERING/GROUNDING
- LARGE, LONGER LIFE SATELLITES
 - NEW INTERACTIONS
 - o SIZE EFFECTS
 - LOW ALTITUDE, HIGHER PLASMA DENSITY EFFECTS

W. C. Brown, Raytheon: "Space Power Magnetron Reliability Review"

When I speak of space power, I'm referring to the Solar Power Satellite System which beams microwave power to the ground in very large quantities. Unlike communications satellites, the output of the tube is not modulated. From the standpoint of reliability, there is some commonality.

I'd like to acknowledge that most of the work has been sponsored by NASA. I think Jet Propulsion Laboratory probably originated the idea of using the magnetron in space power systems. I think they were motivated by the realization that when you use tubes in million lot quantities, you had better have a low production cost.

A solar photovoltaic array continually faces the sun. The DC power from it is converted to microwaves and beamed to earth where it is converted to DC by a rectenna. There is a pilot beam which tells the antenna where to point. The frequency is 2.45 GHz, which has good transmission through the atmosphere, rain, and snow. The power level is about 5 gigawatts. The system is reliable, on the air over 99% of the time (except for eclipse periods), in distinction to terrestrial systems, like nuclear power, which do not exceed 85% availability.

Heat dissipation is important, from power conditioning and the microwave generation. We have to radiate waste heat to space. We have a compact package, using a pyrolytic graphite radiator, rather than an active cooling system, because we want a 30-year life.

The microwave oven magnetron has evolved from a point, about 20 years ago, where it cost \$200 and weighed 20 lbs. At present it weighs a pound and a half and costs less than \$25, even with inflation. The guts of this, without the cooling radiators, weighs 0.8 lb, and puts out nominally 600-700 watts, although I've had them up to kilowatts cw. It has the magnets inside of it. The heat is conducted through the shell. In the 300° region, where we want to operate, it has twice the conductivity of copper, but only one third of the weight. It has an emissivity of 0.96 and a pressure so low that it's not a consideration.

If you operate at high temperature, you take advantage of the fourth power radiation law. With solid state devices, operating at 350°C, you get 30 kilowatts per square meter. Tubes have quite an advantage.

We have had a program of looking at magnetrons as amplifiers. How long will the cathode live? If you take a cooker magnetron and turn the heater off, then the tube is not only very quiet, but the cathode runs cool. The carburized thoriated tungsten cathode, heated by the back bombardment of electrons, a self-regulating process, can operate for tens of years provided you have a good vacuum and no ion

bombardment of the cathode. For the space tube, the choice of wire diameter, depth of carburization, cathode temperature and current can be chosen so that you can get well over a hundred years of life.

The magnetron would be used with a circulator as a directional amplifier, typically with 20 dB gain, 10 watts of drive and a kilowatt output, with a bandwidth of 15 megahertz, where the noise and efficiency are nearly constant over that bandwidth.

We are designing for Marshall Space Flight Center an array with sections putting out 5 or 10 kilowatts. For reliability factors, such as the change in magnet strength, you compensate by having output references and a feedback control system for phase and amplitude. You supply some power to a buck-boost electromagnet to adjust the tube. With the buck-boost magnet, you can tolerate a ± 20 percent variation in the output of the photovoltaic solar array, so that replaces power conditioning.

EDITOR'S NOTE: No questions.

SESSION IV - SPECIFICATIONS AND QUALITY ASSURANCE

Michael L. Kahn, Hughes Electron Division: "TWT Vacuum Integrity Screening Techniques"

Until recently there has not been a reliable, repeatable, non-destructive test technique to measure the vacuum in a finished tube. The purpose of this (new) test is to screen tubes prior to shipment. We call it the ion pressure test.

Alternatives: Helium leak detection requires the tube to still be on a vac-ion pump. Mass spectrographic analysis is expensive and can't be done on a packaged tube prior to shipment. In the ion-pressure test, we use the tube itself as a modified Bayard-Alpert ionization gauge, not a new technology, but a new use for it. We have also used the standard cathode activity test, (time to knee) prior to and after a shelf period, but that is not as sensitive.

The ion-pressure test is non-destructive, fast (about 30 minutes), inexpensive (less than \$1000 in parts), and the data interpretation is simple. The test is repeatable and accurate--within 50% of a residual gas analysis.

You need three power supplies: filament, 150 Volts positive on the anode, and 200 Volts negative on the cathode. You need a picoammeter and a microammeter on the anode current. Also a shielded box.

The test is good down to 10^{-9} Torr. Comparative data from residual gas analysis (thanks to Oak Ridge and Aerospace Corporation) and the ion-pressure test shows agreement within about 30%. We only have a calibration factor on one tube type. The data is repeatable. From 594 tube measurements, typical pressures are in the 10^{-8} range.

The measurement is based on the pressure peak, maximum current with associated maximum anode current, shortly after turning on the cathode heater.

We have looked at the effect of gas on oxide cathode life. When pressures degrade past 10^{-6} , the cathode degrades, as shown by time to knee measurements. It can recover.

Summary: We now have available a repeatable non-destructive test for verifying vacuum integrity.

Q: Can you tell the difference between a vacuum leak and gas evolution?

A: The pressure will continue to increase if it is a leak, whereas it tends to go down with operation if the problem is gas evolution.

Q: How do you distinguish the measurement from leakage current?

A: The leakage is in the range of low nanoamps; we can subtract it out.

Q: There used to be a technique of varying the primary current and varying the voltages to differentiate between gas leakage and spurious emission from other electrodes. Have you done any such variation?

A: No, but we have excellent agreement with the residual gas analysis.

Q: On your controlled oxygen leaks, have you used other gases?

A: No, we just did it with two tubes with oxygen.

Q: You indicate 10^{-8} is satisfactory. Did you discover what pressure is unsatisfactory?

A: Pressures in the 10^{-6} or higher range degrade cathodes; pressures below that don't seem to have any effect.

Tom A. Appleby, Hughes: "Improved High Voltage Screening Tests for Space TWTs"

The reliability of the high voltage system is a strong function of the derating relative to the partial discharge inception voltage, the thermal stresses on the system, and the mechanical stresses on the system. Our experience with the DSCS II amplifiers, in a lab ambient life test, shows a failure rate of about 1% per 1000 hours. The data from orbit show: (1) at higher voltage there is reduced margin, and (2) in the vacuum environment of the orbit, there is reduced tolerance to that reduced margin. Data with different amplifiers in the same orbital environment is consistent with this.

We used a hi-pot test, where we apply the voltage, pump down to vacuum, dwell, and then vent back to ambient. For tubes of less than 2000 volts, we use 100% margin; for tubes over 2000 Volts, we use 150% of nameplate voltage. The pass criterion is no trip-offs. The discharge detector is sensitive to 250 nanocoulombs with a time constant of 10 milliseconds. This is an order of magnitude more sensitive than pre-1977 tests. It's arbitrary. We don't know what the damage threshold is, but this test has been successful in identifying defects.

The DSCS 20-Watt tubes showed a sensitivity to temperature, they tripped-off during the cool down. To screen tubes which may be sensitive we have the TV (thermal vacuum) hi-pot, using a thermal plate to exercise the tube over the range of environments it would see in the system.

The Biddle test is very sensitive. We don't have a pass criterion; we get discharges from the leads, etc. We have no flight experience with which to calibrate. We've introduced an improvement, using equipment built for us by the James Biddle, Co., and Aerospace has built a machine. This is the Multichannel Counting (MCC) Biddle test. It uses a multichannel analyzer, a pulse height counting technique, and we can characterize the number of counts per unit time in a series of partial discharge ranges. That gives a quantitative measure for any particular tube.

Under the sponsorship of SAMSO, we have a PRAM contract for an improved hi-potter. The goal was to improve sensitivity to orders of magnitude from the current 250 nano-coulombs. We'll count in three channels, 1-10 nanoCoulomb, 10-100 nanocoulomb, and 100-1000 nanocoulomb ranges, with an improved time constant of 10 microseconds rather than 10 milliseconds. This forms a bridge between the extremely sensitive Biddle test and the historical hi-pot test.

EDITOR'S NOTE: (Discussion of pictures of equipment. Discussion of data on MMC Biddle test, not very meaningful without slides.)

The high voltage encapsulation system is sensitive to the (thermal) environment under which it is being tested (with higher discharges at lower temperatures).

For long term confidence, we are attempting a lifetest under the cycled environments the amplifier would see in space. (Some description of equipment.)

What we require is a simple go, no-go test which includes the range of environments the unit will see in the systems. We don't know quantitatively whether our present criteria are close or not.

Outside of screening tests, we must reduce the electrical, thermal, and mechanical stress in our designs. Future designs should go as far as we can to eliminate solid encapsulation systems.

Q: Do you have examples of problems in operational systems related to a lack of high voltage screening?

A: The first one that comes to mind is DSCS II, where we did wring out some additional failures (with additional testing).

Q: In orbit failures?

A: There have been several where the signature best fits a high voltage breakdown.

Q: Have any of the failures passed the screening tests?

A: We have had failures show up at the integration level, where they experience more thermal-vacuum cycles. We have had tubes fail the hi-pot which work very well in the amplifier, which suggests that the trip level in the hi-pot is much more sensitive than the power supply.

Q: How do the present hi-pot tests for tubes compare with those for EPCs?

A: I can't answer that. I'm not familiar with the testing at the EPC level.

Q: You made a point that the failure rate for 4000 Volt tubes is higher than commercial C-band tubes under 2 kV, but is the environment the same?

A: I'm not that familiar with what the satellites see relative to their thermal cycling. The half-watt tube DSCS is very similar to the Intelsat tube, but the commercial tubes (amplifiers) have a factor of 4 or 5 lower failure rate.

A. S. Rostad, Hughes: "Evolution of High Reliability Electronic Power Conversion Designs for Space Applications"

Comments on the development of TWTAs over the last 11 years or so: Back in '69 we got involved in amplifiers for DSCS. The design had a buck regulator and as many telemetries as possible. The result was a complicated system which was difficult to troubleshoot and repair. The boxes were crammed with electronics, stud-mounted transistors and other components which were available at the time, with lots of cables. The module can't be tested until it's all together. Then it gets a Biddle test, at 1.5 times voltage, in air, to verify spacing before it is potted.

The workhorse for several applications is the same power supply in a different box. It's not as efficient as newer designs. Telemetries, particularly in the high-voltage section, are a complication and they are fairly heavy.

Newer designs: For commercial business the company looked at at second-generation designs. One development was a regulating converter, which is patented under the name Venable converter, after the designer.* We have a cathode post-regulator which makes it more flexible to program voltages. We have an active cathode ripple filter, which allows a reduction in capacitance and stored energy.

These amplifiers, basically, have only one telemetry output.

We have a series regulator that is only in the circuit during warm-up; then all voltages are handled by the single regulating converter.

The mechanical design is improved, smaller, lighter, easier to test in sections. We got away from foam encapsulation. We got a better package for the transistors. In the latest designs we have practically eliminated interwiring. (Many illustrative slides.)

We are working at getting better parts screening, advertising some of the common circuits, and continuing research on potting compounds. We are looking at other topologies of converter to reduce stresses from transistors. We need a better model for the thermal and mechanical stresses in the potted module during thermal cycling.

Q: Impact on reliability of EPC for TDMA communications?

A: The lower the rep rate for TDMA, the more difficult it is, especially with multiple depressed collectors, to keep the ripple out.

Q: What type of testing, relative to Tom Appleby's description?

A: We used the Biddle test for all the magnetic components, used the corona inception test, too. Now, we do more screening (than we used to) on the EPC level, and longer thermal-vacuum cycling. Temperature cycling is a very good screening test.

Q: Advantages of the voltage multiplier circuit versus transformer?

A: It's a trade-off. Presently we're using transformers which reduces the parts count. I see a problem in the reliability of small capacitors.

*H. D. Venable

Capt. James M. Jemiola, AFML/MBE: "Space Qualification of Potting Compounds"

There is a contractual program with TRW, just commenced; Walter Hudgins, TRW/DSSG is the program manager. The program will look at high voltage design and breakdown, encapsulant failures, and intrinsic material property deficiencies. It may be that we are inducing (by overstress) on the ground those failures we see in orbit. Perhaps we are excessively acceptance-testing TWTs. We'll look at solid encapsulants (rather than gases or liquids). We'll look at thermo-mechanical and electrical considerations of the design of TWTs and power supplies. We'll use a unified analysis, define shortcomings. Then we will analyze a component iteratively until we know how to predict electrical or mechanical failure modes, presupposing that there are potting material failures. As a follow-on, if need be, we'll get into basic material development and/or man-tech program on processing.

Q: How do you feel you can extrapolate from a particular design component?

A: We would like it not to be design-unique. We'll use both a TWT and a high voltage component, a connector or power supply.

Q: How about processing techniques?

A: We'll come out with recommendations about possible deficiencies. Perhaps material modification, fillers, resin ratios, cure techniques. We're not formulating completely new polymer systems. We'll go after component design. Perhaps certain design features make potting fail; perhaps present designs can't be potted.

EDITOR'S NOTE: (Questions regarding vu-graphs)

Q: Advantages of potting versus vacuum.

A: Some of the disadvantages of no potting are the lack of mechanical support during vibration and what happens if loose particles got in there, but it's hard to make that decision.

Q: Effect of temperature cycling on crack propagation?

A: It's complex, and it's not intuitively clear. You have to do a careful analysis.

Q: Is one way (vacuum, solid, gas, liquid) better than another?

A: You can probably make any one of the methods work; you have to look at systems considerations.

A. Tweedie, GE: "Electronic Modules as Structures"

POTTED ELECTRONIC MODULES AS STRUCTURES

- NEARLY ALL FAILURES OF HIGH VOLTAGE MODULES ARE RESULT OF SOME TYPE OF MECHANICAL DEFECT OR FAILURE (VOIDS, UNBONDED AREAS, CRACKS, INCLUSIONS)
- MECHANICAL DEFECTS AND FAILURES RESULT FROM INADEQUATE DESIGN AND/OR MATERIAL SELECTION, OR INADEQUATE PROCESSING.
- THE SOLUTION TO THESE PROBLEMS LIES IN APPLICATION OF ORDINARY STRUCTURES CONSIDERATIONS TO THE DESIGN AND PROCESSING OF ELECTRONIC MODULES.

PROCESSING

- FOR VACUUM USE MUST HAVE VOID FREE CASTINGS WITH GOOD ADHESION TO ALL SURFACES.
- VACUUM PROCESSING IS A MUST
- SURFACES MUST BE PROPERLY PREPARED FOR ADHESION
 - MANY DIFFERENT SURFACES
 - CAN NOT DO USUAL SURFACE ETCHING, ETC.
 - THEREFORE, PART & COMPONENT SELECTION MUST BE DONE WITH ADHESION IN MIND
 - (AVOID TEFLON, SILICONES, OILY MAGNETICS)
- CURE SCHEDULES TO MINIMIZE INDUCED STRESS

PROCESSING - SUMMARY

ALL KNOWLEDGE EXISTS OR CAN BE READILY OBTAINED FOR SATISFACTORY PROCESSING OF HIGH VOLTAGE MODULES. THE PROBLEM IS, THAT IT IS FREQUENTLY NOT APPLIED EARLY ENOUGH IN THE DESIGN CYCLE TO PREVENT LATER PROBLEMS.

DESIGN AND MATERIAL SELECTION

- MECHANICAL DESIGN OF ELECTRONIC MODULES IS BASICALLY IN THE CUT AND TRY MODE OF ENGINEERING OF 75 YEARS AGO.
 - PACKAGING ENGINEER LAYS OUT THE COMPONENTS TO OCCUPY MINIMUM SPACE AVOID CIRCUIT PROBLEMS, MEET MINIMUM DIELECTRIC SPACING CRITERIA, AND INTUITIVELY REDUCE MECHANICAL STRESS
 - TEST MODULES ARE MADE AND TESTED (THERMAL CYCLES) UNTIL SUCCESS IS ACHIEVED.
(NO FAILURES AFTER MANY CYCLES)
 - MODULE IS PUT INTO PRODUCTION.

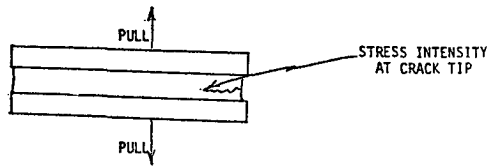
POTENTIALLY GLARING GAP IN THIS DESIGN-TEST CYCLE

A LOOK AT THE WAY TYPICAL POTTING COMPOUNDS FAIL SHOWS THAT SHORT TERM TESTS MAY NOT SHOW UP DESIGNED-IN MECHANICAL OVERSTRESS. THEREFORE, MODULES MAY FAIL IN LONG SERVICE DUE TO INHERENT DESIGN FLAWS.

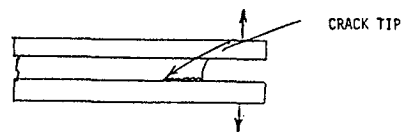
FOR RELIABLE POTTED MODULES FOR LONG SERVICE THE FRACTURE MECHANICS OF THE POTTING MATERIAL AND THE STRESS IN THE MODULE MUST BE CONSIDERED.

WHAT IS LONG TERM VISCOELASTIC FRACTURE?

EXPERIMENTS WITH VISCOELASTIC MATERIALS



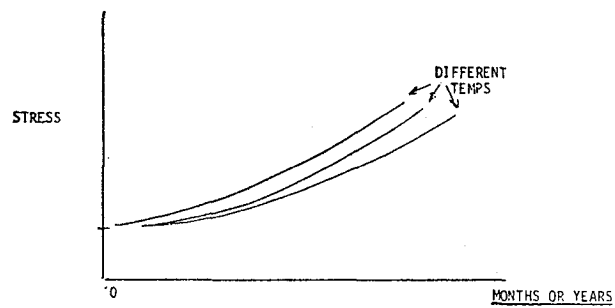
CRACK PROPAGATION IN BULK POLYMER



ADHESIVE BOND TEST - CRACK PROPAGATION ALONG AN INTERFACE

MEASURE RATE OF CRACK PROPAGATION VS. STRESS INTENSITY.

RESULTS



PROPAGATION RATE
($f \log \frac{1}{T}$)

TIME TO FAILURE CAN BE MONTHS OR YEARS

DESIGNS WITH OVERSTRESSED MATERIAL MAY NOT SHOW UP
FOR LONG PERIODS OF TIME.

RELATION TO TWT'S

TWT FAILURES FIT A PATTERN THAT CAN BE EXPLAINED BY THIS PHENOMENON.

- MANY FAILURES AT SAME LOCATION
(IMPLIES SOME SYSTEMATIC MODE)
- LOCATION IS PROBABLY HIGH STRESS POINT
- FAILURES OCCUR IN APPARENTLY "GOOD" MODULES
- FAILURES OCCUR AFTER LONG PERIODS OF TIME

WHAT IS TO BE DONE?

1. DEMONSTRATE THE PROPOSED FAILURE MECHANISM

- MEASURE MATERIAL PROPERTIES NECESSARY FOR THE ANALYSIS
 - VISCOELASTIC CRACK PROPAGATION RATE AND THRESHOLD VALUE
 - THERMAL COEFFICIENT OF EXPANSION
 - POISSON'S RATIO
 - CURE SHRINKAGE
 - THERMAL CONDUCTIVITY
 - SPECIFIC HEAT
- STRESS ANALYZE THE CURRENT DESIGN
- DETERMINE IF STRESS IN CURRENT DESIGN IS AT OR NEAR THRESHOLD VALUE FOR CRACK PROPAGATION BY ANALYSIS AND MODEL EXPERIMENTS

WHAT IS TO BE DONE? (CONTINUED)

2. USING TECHNIQUES DEVELOPED ABOVE:

- SEEK SUITABLE POTTING MATERIAL WITH CRACK-PROPAGATION THRESHOLD ABOVE STRESS IN CURRENT DESIGN
- MEASURE PROPERTIES OF STATE-OF-THE-ART POLYURETHANES, SILICONES, FLEXIBLE EPOXIES.
- FIND HOW TO MODIFY THE GEOMETRY, IF NECESSARY, TO ACHIEVE A SATISFACTORILY LOW STRESS LEVEL.

POTTING MATERIAL FAILURE MECHANISMS

- SLOW OPENING OF BOND LINE BETWEEN POTTING AND STRUCTURE.
- SLOW PROPAGATION OF CRACK THROUGH THE BULK POTTING MATERIAL.

THESE MECHANISMS ARE FUNCTIONS OF:

- 1) TIME
- 2) TEMPERATURE
- 3) STRESS LEVEL

TIME-DEPENDENT FAILURE MECHANISMS

- **FLAW INITIATION**

CREEP RUPTURE (STATIC FATIGUE, STRESS RUPTURE)

BREAKING OF MECHANICAL BONDS UNDER A CONSTANT STRESS FIELD.

STRESS CORROSION

SURFACE FLAWS PRODUCED BY CHEMICAL REACTION WITH SURROUNDING ENVIRONMENT.

RATE OF FLAW INITIATION IS FUNCTION OF

STRESS LEVEL

TEMPERATURE

- **CRACK PROPAGATION**

REQUIRES A FLAW OF "CRITICAL" SIZE

RAPID PROPAGATION (CATASTROPHIC FAILURE)

GENERALLY ASSOCIATED WITH BRITTLE FRACTURE.

SLOW PROPAGATION

GENERALLY ASSOCIATED WITH VISCOELASTIC FRACTURE.

PROPAGATION RATE DEPENDS HEAVILY ON:

STRESS LEVEL

TEMPERATURES

TIME SCALES

	1 DAY	1 WK	1 MO	1 YR	3 YR	10 YR
SECONDS	86,400	604,800	2,592,000	31,536,000	94,608,000	315,536,000
MINUTES	1,440	10,080	43,200	525,600	1,576,800	5,256,000
HOURS	24	168	720	8,760	26,280	87,600

CRACK PROPAGATION DATA

- EXISTING DATA OBTAINED AT ELEVATED TEMPERATURES TO INCREASE CRACK VELOCITY.

- WLF TIME-TEMPERATURE EQUATIONS USED TO OBTAIN THE ROOM TEMPERATURE CRACK VELOCITY.

10^{-7} -- 10^{-6} IN/HR

SOLITHANE 113 (POLYURETHANE ELASTOMER)

- AFTER 1 YEAR, CRACK LENGTH WOULD BE AT LEAST 1-10 MIL.

PROBLEM IS AGGRAVATED FURTHER BY TWO PHENOMENA.

- 1) SMALL INCREASES IN STRAIN PRODUCE LARGE INCREASES IN CRACK VELOCITY.
- 2) AS CRACK GROWS, STRESS INTENSITY INCREASES, ACCELERATING THE PROCESS.

CRACK WILL GROW UNTIL MATERIAL SEPARATES.

PROGRAM OBJECTIVES

- DETERMINE THE PROBABILITY OF MECHANICAL FAILURE OF DSCS-III TMTS DUE TO POTTING FAILURE.
- FIND A COMBINATION OF MATERIAL AND GEOMETRIC DESIGN WHICH WILL PRODUCE A LONG-LIFE TMT.

GE APPROACH

- CHARACTERIZE MATERIALS.
- -STRESS ANALYZE THE DESIGN.
- EVALUATE FAILURE CRITERIA.

- RANK MATERIALS ACCORDING TO VISCOELASTIC CRACK PROPAGATION PARAMETERS.

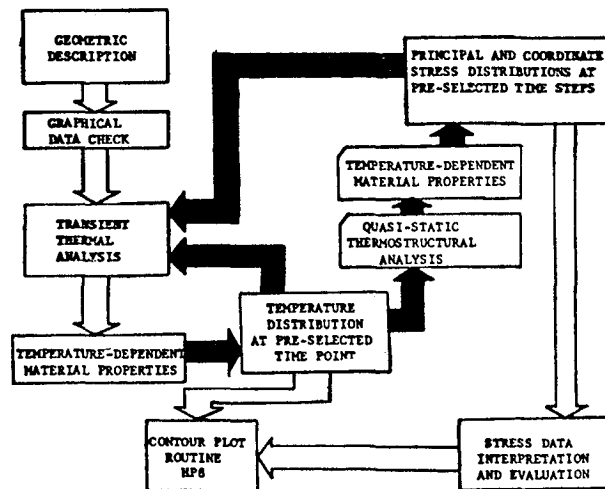
MAY FIND A MATERIAL WHICH WITHSTANDS CURRENT STRESS PATTERNS.

- STUDY GEOMETRIC EFFECTS ON STRESS DISTRIBUTIONS.

MAY FIND SIMPLE GEOMETRY CHANGE WHICH SUBSTANTIALLY REDUCES STRESS CONCENTRATIONS.

- USE COMBINED MATERIAL/GEOMETRY TO ESTABLISH A DESIGN WHICH MEETS 10-YEAR LIFE.

GI FINITE ELEMENT CODE



EXPECTED RESULTS

- STRESS DISTRIBUTIONS FOR CURRENT GEOMETRY UNDER EXPECTED THERMAL CYCLE.

TO BE COMPARED TO MATERIAL CRACK PROPAGATION THRESHOLDS.

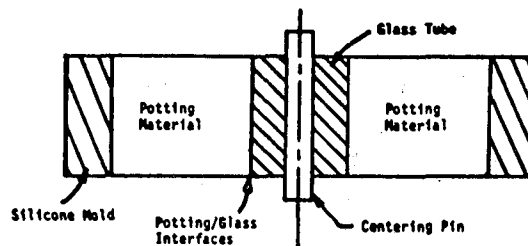
- STRESS DISTRIBUTIONS UNDER GEOMETRIC DESIGN VARIATIONS FOR SAME THERMAL CYCLE.

AGAIN COMPARED TO MATERIAL CRACK PROPAGATION THRESHOLDS.

EXPERIMENTAL VERIFICATION OF ANALYSIS

- PHOTOELASTIC EXPERIMENTS

1) STANDARD ASTM CALIBRATION TECHNIQUES



—DUE TO SEVERAL NONLINEAR EFFECTS WHICH OCCUR DURING SOLIDIFICATION OF THE POTTING MATERIAL, QUANTITATIVE CALIBRATION IS VERY DIFFICULT.

—RADIAL STRESS IN GLASS CAN BE OBTAINED IN PHOTOELASTIC EXPERIMENT.

- MECHANICAL & OPTICAL PARAMETERS FOR GLASS ARE CONSTANT OVER THE TEMPERATURES RANGE OF INTEREST.

—STRESSES IN POTTING MATERIAL ARE THUS KNOWN AT THE INTERFACE.

—SIMPLE GEOMETRIES MODELED BY BOTH ANALYSIS AND PHOTOELASTIC EXPERIMENTS TO BE COMPARED FOR ANALYSIS VERIFICATION.

OTHER ACTIVITIES

- HV STRESS ANALYSIS
 - IDENTIFY CRITICAL AREAS FOR STRESS ANALYSIS
 - ASSURE CONSERVATIVE DESIGN
 - RF PROPOSED CONFIGURATION CHANGES
 - IN MATERIAL SELECTION
- MATERIALS HV TEST
 - CHARACTERIZE BREAKDOWN VS. TEMPERATURE-TIME EXPOSURE
 - VERIFY CONSERVATIVE VOLTAGE STRESS
- EVALUATE CONFIGURATION IMPROVEMENTS
 - ONLY MINOR CHANGES CONTEMPLATED
 - REDUCE MECHANICAL STRESS
 - CONSERVATIVE HV DESIGN

SUMMARY AND CONCLUSIONS

1. CURRENT "CUT & TRY" METHODS FOR DESIGNING POTTED MODULES ARE NOT SATISFACTORY FOR LONG LIFE DESIGNS.
2. "TRY" EXPERIMENTS MAY NOT REVEAL VISCOELASTIC FRACTURE PROBLEMS. "BURN IN" MAY ACTUALLY SHORTEN LIFE WITHOUT ELIMINATING POTENTIAL FAILURES.
3. QUANTITATIVE ANALYSIS AND DESIGN TECHNIQUES ARE NEAR AT HAND. ALL THAT REMAINS IS TO VERIFY AND APPLY THEM.
4. THE PROPOSED PROGRAM WILL PROVIDE A RELIABILITY ANALYSIS OF CURRENT POTTED TWTs.
5. THE PROGRAM WILL ALSO DETERMINE HOW TO CHANGE MATERIALS AND/OR GEOMETRY TO ACHIEVE THE 10 YEAR LIFE FOR DSCS III.

Vincent R. Lalli, NASA-LeRC: "Traveling Wave Tube Reliability Assurance"

EDITOR'S NOTE: Vince Lalli spoke about traveling wave tube reliability estimates, based on the CTS tube testing. He predicted, on the basis of elegant mathematical analysis, that the tube might fail sometime between the design life of two years and the time when hell freezes over. In fact, the one CTS tube which flew in space was turned off, with the rest of the satellite, after roughly twice the designed lifetime. Its cathode was showing a barely detectable loss of emission.

Q: How did you arrive at the piece-part failure rates?

A: We have an extensive library: MILSTD 217A and B, literature searches, field data. On new inventions, we had to use engineering judgment.

Q: What was a relevant failure?

A: When we could explain it as an instrumentation failure or something not chargeable to the output stage tube, they were not relevant. The one relevant failure was when the body current started to increase.

Q: Was lifetest run in a vacuum?

A: It would have been best in vacuum. We did run a number of thermal vacuum tests, but the life tests were in air conditioned rooms.

Q: Elaborate on failure mode criticality analysis.

A: The project office did a lot of R&D on those particular problems.

COMMENT: (Dr. Kosmahl) The tube was subjected to costly testing--bake-out, especially, in vacuum. There were problems with the cathodes (Litton Phillips B) but the poor ones were disqualified. But after almost four years, the degradation is only 1 mamp out of 75.

EDITOR'S NOTE: (For additional information, see NASA TM X-73541, V. Lalli and C. Speck, "Traveling Wave Tube Reliability Estimates, Life Tests, and Spaceflight Experience" Jan 1977.)

Boyd Israelson, Watkins-Johnson: "High Reliability TWT Power Supplies, Packaging Concept and Test Results"

The power supply addressed originated in 1975 and is built in 10W and 40W versions for the DSCS II and DSCS III and will be used in other satellites. It is distinctive in that, in order to save weight, conventional solid potting was not used. Instead, a thin conformal coating is used, principally to keep it clean, though the coating does help in heat dissipation for certain components.

For surface high voltage creepage, the criterion was a distance in inches equal to one fourth the square root of the voltage in kilovolts. Example: 4 kilovolts requires $\sqrt{4}/4$ or 1/2 inch separation. The breakdown criterion was 10 Volts per mil. They could accommodate a loose particle (in zero-g) of 0.072 inches diameter without malfunction.

EDITOR'S NOTE: (Several slides of the specifications and physical layout were shown.)

(Bob Levitzi described the environmental testing.)

They have proven they can make a supply which works perfectly in vacuum without potting. However, the avoidance of critical pressure during the testing (problems of outgassing and bake-out) demands care during the qualification tests. They observed order of magnitude differences in pressure as measured by different gauges in the same vacuum chamber. The ion gauge itself was a source of contamination, with ions accelerated toward the power supply. The lesson: turn off the ion gauge when you turn on the power supply, but preserve the loss-of-pressure abort capability by using a shielded ion gauge in the manifold, close to the pump. Also, run the supplies with their covers on.

James Schram, of Watkins-Johnson, concluded the session with a discussion of space TWT reliability, expressing some observations and opinions. Reliability generally reflects the engineering of the device, plus process and design execution. The top priority must be reliability improvement, rather than specification or performance improvements. We have assumed reliability in the absence of known problems, the passive approach. The contract structure must encourage the active pursuit of reliability. Time is necessary, but in short supply.

Some of the major concerns are cathode life, vacuum and high voltage integrity, focusing stability, thermal and mechanical design integrity, and process controls. A TWT is series problem, many details in series, any one of which can cause failure. A qualification model does not insure reliability. It shows what can be done if it is executed properly. Every play in football is capable of a touchdown if executed properly.

Flight units follow closely--where's the reliability analysis going to take place? Schedules are fixed and tight. Cost minimization is stressed. We presume what the failure mechanisms will be, but the real problems may go undetected. Effective solutions are often precluded by time factors, the emphasis on keeping to a tight schedule (and a fixed price). We can't make house calls in space.

What to do? An active approach to reliability: verify, don't assume. Absolute knowledge of the execution of designs and processes. A separate technical team to evaluate quality control, with actual stress test, dissection, and autopsy of random flight TWTs. Self-inspection is not the way to do it. Programs must be structured around reliability, not the ultimate in efficiency. True value engineering means leaving nothing to chance, even though that costs. The age of buying by low bidding is fading away; the buyer gets what he pays for.

Specifics: Do all the screening tests in thermal-vac. Cathode activity tests. Step stress tests to destruction, to learn as much as you can about good flight hardware, not just to prove it will pass the requirement. Voltage breakdown tests, focusing stability tests, cycling--all destructive. It means building a few more units. Maybe our best people should be the independent autopsy team, not in the roles of designing or fabricating. New techniques--surface analysis, residual gas analysis, etc. can be applied.

A slide showing a microscopic inclusion in a metal part was shown as an example of usually undetected defects. Another experiment showed fluorine contamination from paper with which parts might be handled.

The prerequisite for reliability is time. Problems must be searched out before they find you, an active philosophy. Use state-of-the-art techniques and expert people. It needs a major commitment by the TWT manufacturers and by those who fund them.

COMMENT: The military should work out a way to make sophisticated equipment available to the TWT builders.

A: We have found independent labs which can provide these facilities at low cost. Most of these facilities actually cost less than a single TWTA.

COMMENT: A program like that will only yield ulcers if it doesn't also provide funding for the corrective actions you find.

A: Hear! Hear!

Q: I shudder at the cost. How, in view of competitive constraints, can you spread the information without funding the program five or ten times?

A: The cost delta may be 50%, but what is the cost of a mission compared with the cost of a device.

EDITOR'S NOTE: (Capt. Bruce LaMartine, AFML, added an unscheduled presentation on the status of DSCS TWTs.)

The DSCS II failures that we had had not been at an alarming rate until about three years ago. Prior to that time we did not do any appreciable thermal-vac testing of our units. We started more extensive thermal-vacuum screening as well as leaving the tubes off for two weeks in orbit to let them out-gas. Of those TWTs successfully screened and successfully launched last fall, there have been no failures.

Just last month we put the lifetest 20W units, which had been running for almost eight years, into the thermal-vac. Two of four failed promptly, apparently with high voltage arcs. For DSCS III, we very recently found out that our thermal-vac screening may not have been long enough. Tubes have failed after two and four weeks continuous vacuum. In that respect we are looking at removing the potting and using an unpotted collector. There are also mechanical problems, but they are fixable. A third area is a serious cathode problem; it has only showed up in the past six months or so, after 2-3 thousand hours. It shows up as a rounding of the knee on the dip test.

For the future we plan to verify and extend the thermal-vac screening. Also, under a PRAM study, we have been looking at cathodes and potting processes. I hope the unpotted collector will relieve our problems in the high voltage area.

Q: Change from oxide to dispenser cathodes?

A: Not for at least four launches, five years, but we are studying them.

Q: About thermal-vacuum screening.

A: The only systematic problems have been in the TWT. Power supply problems have been one of a kind and usually fixed.

Q: About h-at processing while tube is on pumps.

A: I don't think we do any thermal testing other than the focusing, which is done over a temperature range--right?

(Inaudible comments.)

SESSION V - PANEL DISCUSSION

Chairman: C. L. "Larry" Jones, TRW/DSSG
E. Illoken, Hughes/EDD
Dr. Fred J. "Bud" Dietrich, Ford Aerospace and Comm. Gp.
James Schram, Watkins-Johnson
Paul Koskos, COMSAT Laboratories
R. E. Alexovich, NASA-LeRC
Dr. Henry Kosmahl, NASA-LeRC

JONES: We might look at the results of the questionnaire that many of you filled out.... Obviously cathodes and high voltage events were of major concern. Re: "Ticking" - there were 22 "yes" out of 50, yes, they had experienced it and to some it was a problem; 6 "no" and 19 "don't know".... This activity on the electrodes makes it difficult to separate the good guys from the bad guys. Any questions?

RON BLEWITT, LOCKHEED: Does the CTS satellite have no potting at all or conformal coating?

ALEXOVICH: The CTS power supply has essentially no potting, except for the transformer, to remove heat. A few wires were glued down at points. There was no potting in the tube.

QUESTION: What kind of guidelines would be needed...so we don't have to concern ourselves about condensibles or debris...which might screw up an unpotted spacecraft?

ALEXOVICH: My bias...experience has been with vacuum as insulation... I firmly believe that is a good way to go. The one problem is removing heat from the transformer. With the ion engines, they tried to make an unpotted transformer. They succeeded, but it was very difficult, with many compromises.

DIETRICH: We're presently, at Ford, building the Intelsat V spacecraft, which has 43 TWTAs; growth versions will have more.... Is it necessarily true that unpotted boxes will have to be bigger? How about DSCS III?

SCHRAM: The W-J EPC has a conformal coating. It's not totally unpotted. I believe at higher voltages you may find an impact with layouts. On CTS, how was the power supply tested if it wasn't able to withstand voltage at atmosphere?

ALEXOVICH: It was able.

SCHRAM: All power supplies may not be able to unless it's considered during design. I think TWTs may be configured for such an approach, but specific tests would have to be done to educate

ourselves...so you don't get localized critical pressures. It would be more repeatable than trying to solve (potting) execution problems which are so workmanship related.

ALEXOVICH: On CTS, certainly we had a larger box, but I don't know how it would compare on weight.

ISRAELSON: For DSCS, we opted for the unpotted design, with a conformal coating as protective surface. The hard potted modules, our traditional approach, would have weighed more and required more structure in order to control resonant frequencies.... The layout did not prove to be a problem.

SIVO: Did you take any added precautions after conformal coating?

ANSWER: The usual tests...atmospheric and vacuum.

OTT, JPL: When you try to integrate several of these things in a spacecraft, what sort of problems? Also, what type of potting was used in the transformer at 11 kV?

ALEXOVICH: All I can remember is that it was a carcinogen, and we no longer use it.

COMMENT: On spacecraft testing with unpotted amplifiers--the greatest problem has been at the EPC level, and the problems have been because of ion gauges and not having the covers on the amplifiers. At the amplifier level, mated with the tube, we have never, ever, even once had an arc. The same holds true for the spacecraft level. The 10-Watt qual's on GE spacecraft are operating perfectly in vacuum. The space vacuum is probably no better than the ground vacuum. Ion gauges on Skylab showed no better than 10^{-5} Torr...so anything that passes our testing should operate fine in space.

ZELEN, RCA: I think the nub of the problem is that we're talking about building dozens at a time and insuring that the first is as good as the hundredth one. (One success may be a happy coincidence.) By definition, we only launch good spacecraft. Many problems are not vacuum-related or even high voltage related.

JONES: Is there a consensus on adequate screening? A day, a week in vacuum?

SCHRAM: Adequate screening must evolve with the program. One thousand hours or two thousand hours only show that a device lasted for that length of time. There can be mechanisms that take years. Perhaps there should be several tests, including the manufacturer, that should be on-going and bridge several programs. Maybe there should be a board or panel--NASA, SAMSO, COMSAT, and other agencies--which have programs to get together and help finance things for their common good.

KOSKOS: We feel fortunate in having an eight-year life, but the standard deviation of two years means you have to have two tubes per channel to get a ten-year life. (Gap in tape.)

DIETRICH: Maybe we, collectively, as an industry have driven ourselves too hard. We should back off and let the designers do it right the first time, without compromises to reduce time, cost, mass, etc. Then the purpose of testing is to show that you are correctly executing a good design.

Many failures in commercial spacecraft seem to be associated with thermal cycling. Why? Is the cathode getting poisoned?

RIVALAN, INTELSAT: The eight-year life we have results in significant operational problems. For Intelsat V, each transponder serves a peculiar role--having 90% of the transponders available is like having a bad satellite. We don't know why we have eight-year life; maybe we got lucky. We would like to understand why, and how to repeat them.

ILLOKEN: I think the screening test is to take care of infant mortality. Acceptance tests shown uniformity. Wearout, or steady state failure rate, is a problem of design. It is a lack of understanding of what is an adequate screening test, to determine marginal hardware, which has gotten us where we are today.

QUESTION: What you are saying is that you can't predict long term trends from short term screening data. On the other hand, that's the only handle we have, on cathodes, for example. Can you suggest some other technique?

ILLOKEN: You can no more predict longevity for a tube than you can by getting a physical say that you will live ten more years. I agree with Paul (Koskos) that the life we have seen for Intelsat tubes is not consistent with classic wearout phenomena. I think the model (for cathodes) is good for predicting diffusion rates, arrival of barium...I think there are other problems lurking in the background. It behooves us to really find out what those other problems are. Then, when you see the tube is normal, then you know the design is built in for life.

KOSMAHL: By 1980, the historical data will be available. By making a statistical study--I hear tubes which work on commercial satellites do not function on DSCS--somebody, the military or NASA, should evaluate all the tubes, study the statistics to try to understand why.

I used to work for Telefunken in 1951; they developed a power tetrode. The tube went into production. In production the tubes lost emission. The company panicked. The chemists could

find nothing. The company lost a lot of money. Finally, after half a year, they changed the vendors for all the cathode materials and sleeves. The emission came; nobody knew how, ever. I understand now, with oxide cathodes for DSCS, the emission disappears. Nobody knows how or why.

I suggest a national bank of materials which have worked well and which could be made available to all U. S. manufacturers, as long as we don't fully understand why some cathodes fail.

ILLOKEN: We have started an effort on a data bank.

COMMENT: What we're doing at Hughes Aircraft, both at the tube division and at the Space and Communications Group, is cataloguing over a thousand tubes. To date we have about 600 tubes catalogued-- 37 design, build, and lot traceability parameters as well as all of the operational parameters, beginning with burn-in of the tubes. That includes the orbital history of the tubes. We're just now in a position to start operating on that data, using a multiple regression technique. It's very expensive, going back through all of those records to make a computer file. We'd like to solicit support from other people.

KOSMAHL: I agree entirely. It seems it is not sufficient to look at tubes from only one company. You could learn more if you study what others did.

ILLOKEN: Research on oxide cathodes stopped 20 years ago, and there aren't many real experts left. The purpose of this data analysis is to find correlations and then have something to direct the experts in the right direction. Watkins-Johnson oxide cathodes are different from our own. We can fool ourselves by trying to compare. We built a lot of tubes in the 60's which lasted 12 or 14 years. It's a matter of finding these elusive parameters.

SCHRAM: There is merit in both approaches. If you are going to handle something statistically, you would have to have complete information. Hughes can analyze Hughes data because they have this information.

SIVO: To what extent will Hughes be able to help the rest of us to understand? Second, is there an appropriate time to make provision to add other data to the data bank, understanding that there may be basic differences? Perhaps I could assist? We've got a common problem.

ILLOKEN: It's very complex, performance in space. Some changes are so small that the normal accuracy of telemetry isn't adequate. A more organized method of getting data back would be greatly appreciated. Thermal cycling. Some curious correlation between degradation and specific channels. We don't understand it.

SIVO: I think we have people here who are users. We should help Hughes get the information.

COMMENT: We have tried. Our operating people make comments about those laboratories in the sky. It isn't practical to have all the telemetry we'd like to have.

SIVO: We've had the same problem.

QUESTION: What is the optimum telemetry?

ILLOKEN: Murphy's law applies to telemetry. It never works when you need it. I haven't seen one good failure in space where you have a good description of what took place. If that's the case, telemetry only adds to the problem by reducing reliability.

COMMENT: On Intelsat V we have one telemetry point from each TWT, on or off.

WILDE, COMSAT: I'd like to suggest telemetry of beam current, helix current, buss current, regulator output voltage, but none of them unless they can be implemented with no impact on the things I can actually get money for.

COMMENT: And channeled directly to the TWTA manufacturers so the operating people don't get nervous when they see the helix current change by 10%.

COMMENT: That's an important point. The more we get, the more we want, until we go too far.

KINAMAN, HUGHES: I'd like at least cathode current or power output to show trends. That's the key. Helix current is very interesting.

SCHRAM: A nice source of data is having something under simulated space conditions on the ground for a long period of time when you can learn everything you want to know about that device. One, without the other (i.e., space plus ground) is a hot dog without mustard.

COMMENT: Let me caution people before you invest in a data bank; it's no good unless you use it. And it costs a bloody fortune to maintain. Most companies will rarely look at the pedigree of a single failure, much less an enormous data bank.

EDITOR'S NOTE: (Some discussion of sources of data other than Intelsat.)

ILLOKEN: ...This data bank turned out to be a very good quality and reliability tool for on-going programs--the screening--to see trends--screening between different programs in real time.

EDITOR'S NOTE: (Discussion about possible NASA or DOD support.)

QUESTION: Jim made a point that a TWT is a hundred or a thousand steps, any one of which can contribute to disaster. How do you maintain discipline in a day when, in general, workers are slovenly?

SCHRAM: It's a matter of company philosophy. Largely it's an education process. Our problem is to make the environment conducive to what we want to do.

QUESTION: What about the extemporaneous process change on the part of a well-meaning engineer?

ILLOKEN: Process changes are serious problem. Our process specs are never changed. They can be added on, but you can't delete anything. Individual programs may have to change, and in that case it has to be documented.

BROWN, RAYTHEON: The tube requirements for SPS and your interest-- we have common interests. The SPS is further along than you may think, and it has political wallop. One common interest is tubes versus solid state. (Tubes are superior in space.) From the standpoint of image, we have a common hunting ground. The second area is cathodes. Cathodes will be very important in SPS. Testing is an area of common interest.

ILLOKEN: We'd like to have your hundred-year cathode.

HANSEN, TRW: I was hoping someone in government would be starting on a handbook of guidelines for designing spacecraft in boxes that would be compatible with each other, addressing materials and venting and cleanliness and the things which have to be done to make such a system (unpotted) work.

SCHRAM: Re: cathodes...want ten year life...dispenser cathodes... coated M-type cathodes. At what point are the users, technical agencies, and manufacturers content to bite the bullet and go to the promising technology which has not yet developed a history, or stick with antiquated technology with recognized deficiencies which might preclude meeting the objective?

When do I use an M-cathode, given that I have one or two with 30,000 hours while I have five or six years of experience on B-type cathodes which show some degradation, and I'm also looking for ten year life?

JONES: The key is that no one can get accelerated life data on cathodes. We need work such as NASA is funding. Then, collectively the tube manufacturers and systems house bite the bullet.

SCHRAM: Should we put dentures in place now?

JONES: No, I wouldn't for an M-type cathode, based on what I know today.

KOSKOS: I'm not convinced we have a technology limit with the oxide cathode in the kinds of tubes we're working with now. Two amps per square centimeter is a different problem, but we're not getting what we should from the oxide cathodes.

KOSMAHL: They are extremely moody and unpredictable. There is still a lack of knowledge. Because the impregnated cathodes are much more predictable, I would not use the oxide cathode.

SCHRAM: What about the B versus M cathode for 1 amp/cm² today?

KOSMAHL: Today we made the decision. The NASA 20 GHz satellite will have an M-type cathode.

SCHRAM: One vote for no, one vote for M?

ALEXOVICH: When we started the cathode life test program we selected the impregnated cathodes because we were looking to higher powered, higher frequency tubes. One of the things NASA can contribute is to demonstrate the M-cathode.

SIVO: We're taking that risk because it's our responsibility to do so. You're aware of the W-J work, which is limited. What would it take to change from an oxide cathode?

COMMENT: We are putting impregnated cathodes in satellites now. They are not without problems. Changing the problems may relieve the boredom of the engineers.

KOSMAHL: Pete Ramins can testify. He has reactivated a tube up to twenty times.

QUESTION: How many years did that subtract from the life?

KOSMAHL: We don't know, but you couldn't do that with an oxide cathode.

KINAMAN: We had to make a decision for SPS. We ended up with Telefunken tubes. The life test data base was only two years on impregnated cathodes, but there were very many of them, so they could prove a very good mean time to

failure. You (NASA) have such a small effort, you don't really have enough to convince me to take a chance. We have problems with both oxide and impregnated cathodes. While the impregnated cathode does respond very well to poisoning, it's not easy to make either. I'm not ready to leap from one technology to the other, though eventually we'll see it. I'd like support for the oxide cathode as well.

SCHRAM: Two years ago you voted B-type. Would you change your mind now?

KINAMAN: I can't comment on the M. The B-type looks excellent, but there are difficulties manufacturing that, too.

SCHRAM: A large number of shortlived samples only helps if the problem is random.

KINAMAN: I'd like to see more government support to get a bigger data base.

DIETRICH: We faced a subtle version of the same thing for Intelsat V. There were conflicting data and opinions--particularly about the degradation with time. We've had no problems with the tubes. There is a current regulator in the power supply. There are Thompson tubes which have been operating more than 10 years, but you have to compensate for the decrease in cathode emission. We're confident the tubes will last as long as the spacecraft does.

QUESTION: How about shut downs?

DIETRICH: I'm not sure any of those were related to the tube and the cathode; EPCs are another story.

ALEXOVICH: In the Watkins-Johnson life test, the Semicon cathode with a different mix showed a shorter life than the B mix. I believe that cathode was used in one of the Thompson tubes. It was predicted to have short life, and it did. I don't think you can say it can't be predicted.

EDITOR'S COMMENT: (Several comments about the lack of validity of diode life tests, but the assertion that some tubes have 50,000 hours, too.)

ILLOKEN: Rarely does a new technology make the old obsolete. There will be a domain where oxide cathodes are preferred and a domain where other cathodes are a better fit. The dispenser cathodes operate hotter. The heater may become a critical item for reliability. The M-type shows tremendous promise. The only worry is the stability of the coating. The B-type is worse than an oxide cathode, in terms of stability, if you don't use a feedback circuit.

SCHRAM: Would you use the M-type in any application today, over the B-type?

ILLOKEN: No problem in ground applications.

DIETRICH: The NASA experimental satellite is the place to try these things and to get data. (Gap in tape.) That's different than a revenue-producing satellite (where the company can lose a lot of money).

KOSKOS: COMSAT is carrying an experiment. I don't think it's out of the question for commercial satellites to carry several experimental channels, including impregnated cathodes and solid state transmitters.

SIVO: In laying out a long term program, what evidence is required to establish a confidence level to get technology into the market place?

COMMENT: Ground based and airborne tubes are a fair way to evaluate a cathode type--it doesn't know whether it's in space or not. Also, it would be nice if we could put to bed whether or not an accelerated life test program for dispenser cathode is valid.

ILLOKEN: One way to answer that is by bringing up another topic. One thing to worry about is the unsophisticated manufacturing of dispenser cathodes. No wonder--they really don't get that much money for their products, to justify investment in quality control, to get the reliability we're asking for. Several places are going to make their own, as we are. In our case, we base our decision on M-type or B-type on in-house life tests. We do not believe in accelerated life test.

COMMENT: Generally the ground, airborne, shipborne results are not available to the manufacturers--a free life test at accelerated temperatures.

COMMENT: If we knew at the beginning of Intelsat V how to turn the thousand of ECM tubes at 2 amps/cm² into 10-year predictions, we would have saved ourselves a lot of trouble. But no one in industry was willing to say, based on 2000 hours for 50,000 devices, it's good for 50 devices for 250,000 hours.

SCHRAM: (A warning against uncontrolled life tests.)

KOSKOS: You don't want a spot design--should know sensitivities to temperature, current density, porosity, contamination, etc. It's rare that a program manager will let these be investigated beyond the needs of his particular job.

SIVO: Does anyone believe we have that kind of data on oxide cathodes?....(Silence).... Sounds like we don't.

SCHRAM: Consider the functional dependency on small variations. Every design should be on a rather smooth characteristic so that when variations occur (e.g., spacings, cathode temperature) the effect is not serious. This type of analysis has never been done adequately. It's a new dimension.

BUCK: If I had \$10M to spend on reliability, how, philosophically, would I decide how to spend it? Better engineers, cleaner clean rooms, process control on materials....Swiss bank account? Is there some rational approach to an investment strategy?

SCHRAM: They're value judgments. I have a bias for the front end--facilities, materials--those areas that affect the vacuum envelope and cathode.

COMMENT: No correct answer. The fundamental objective is not to make the best product. It's to make money.

KOSMAHL: Some things can't be judged by profit--national security. What and how should the problem of reliability be approached?

ILLOKEN: We have to make a buck. The space business is not that big, and cyclic. The biggest problem is maintaining an adequate staff.... It helps to segregate the space activities from the nonspace activities (because the philosophy of manufacture is so different). We'd like to see some more money flowing in.

(General assent.)

SIVO: What we need to do is put together the rationale for what the program ought to be.

SCHRAM:We must put money into cathode facilities that will make cathodes and the information from those cathodes available to all--my choice for highest priority.

KOSMAHL: How about a national materials bank?

SCHRAM: Yes. More and more materials supply is a problem. A good idea, difficult to implement.

COMMENT: Perhaps industry could use a general spec for dispenser cathodes--vital parameters--particle size, density, porosity, purity, etc., where the physical characteristics could be known and prescribed.

SCHRAM: It's all part of the same package.

OHLINGER, SEMICON: We're not unaware of your needs. We've begun to move toward quality control. I would encourage (government) funding to support these controls. We intend to do it... but it's going to cost more money than we have.

COMMENT: We need a life test program with sufficient cells so we can test cathodes of different sizes, temperatures, and current loadings so we can get confidence in the laws of extrapolation and perhaps establish to what extent accelerated life test is valid.

DOMBRO, W-J: Question about proprietary processes and techniques and conflict with desire for uniform, documented devices.

COMMENT: Even mix ratios aren't agreed on.

COMMENT: The problem is the sorting of the particles so there is uniformity, the doping, the assurance that infiltrant is properly removed....

COMMENT: Perhaps we have to launch twice as many satellites as we'd like to. I'm not sure we know where we can put the money (e.g., to solve cathode problems--but we can put up redundant satellites).

KOSMAHL: Many cathode problems could have been avoided had people used materials with a proven history.

COMMENT: I suspect there would be reluctance to make any changes from what you, as a tube manufacturer, know works.

SCHRAM: But, of course, you begin experimentally. You must prepare for the future today. With regard to the concern about launching more satellites rather than going for more life and reliability, I think the problem is very solveable. I think the cost is a drop in the bucket, comparable to the cost of amplifiers for a single mission. But the problem is a little too big for one group or one person to chew. As a result, it doesn't get attached; the not-my-job philosophy. That's where some benevolent dictator is going to have to make the right decisions.

EDITOR'S NOTE: (Some discussion of cure for cancer versus cure for cathodes.)

ISRAELSON: We're looking for the least cost entity to throw money at to solve the problem. Building more satellites is not the economic way to do that, and perhaps not building more TWTAs. If we can build more cathodes....(Lengthy comment on cyclical nature of business and the need to keep a well-trained and motivated crew together. A plea for production continuity.)

COMMENT: It's important to keep the production continuity. Second point, where should the money go--in parallel, not in line with production. Sure as hell there's going to be a problem, and the priority program will run right over (the people and resources devoted to reliability improvement).

ILLOKEN: What happened to redundancy in the spacecraft? If a channel is worth a million dollars per year, isn't it worth an extra tube?

QUESTION: (To Henry Kosmahl) What is the status of the cold cathode?

KOSMAHL: It is definitely not ready for space use. When we transfer the cathodes (from SRI) to a real gun structure, we have difficulties with arcing and so forth, not necessarily related to the cathode. Probably five years before I would risk one in space.

EDITOR'S NOTE: (Mention of other work, different types of cold cathode, supported by Air Force Avionics Labs, also some work of NRL. Some optimistic comments.)

ENGLEMAN, HUGHES: (Plea for accelerated testing. Hughes is buying Telefunken TWTs of uncertain life, wish they could be quickly tested. Is it impossible?)

COMMENT: No, not impossible. One approach would be to test an incredibly large number of cathodes under various conditions, the brute force method, very expensive. The other approach would be to try to understand the process. We know precious little about the nature and kinetics of the reactions in that barium aluminate mix and the interaction with the cathode matrix.

SCHRAM: We can't do accelerated life test because we don't understand the physics and chemistry involved. We need fundamental research.

EDITOR'S NOTE: (Discussion of bounds on life tests and inferences to be drawn.)

LONGO, HUGHES: A great deal is not known about the fundamental physics. Most life tests have been aimed at qualifying a device, not looking at the physics. We need tests with a wide range of parameters to begin to pull out the underlying physics--work function, temperature, etc.

COMMENT: Relative to redundancy. Apparently RCA and COMSAT General have made the decision to have every tube in service rather than derive no revenue at all from half of them.

QUESTION: If you have a three to one range in tube lives, how can you plan your redundancy?

(Request for conclusions.)

JONES: It has been a useful two days. The dialog should continue.

CONNOLLY, NASA-LeRC: Half the respondents didn't know what ticking is. Enlighten them?

JONES: Ticking is irregular fluctuations in currents, also called helix jitter. My opinion is that it's not serious if it's regular and of reasonable amplitude, not causing serious changes in rf output power. If it's irregular and deep, it looks like high voltage activity. How does one separate benign jitter from dangerous high voltage activity?....Twenty or thirty people in this room have spent, collectively, a few thousand hours on this subject in the last year or two.

COMMENT: It's necessary, when a high voltage power supply is going to be potted, to do a complete mechanical and thermal analysis to make sure it will stay potted. Alternatively, it's possible to make unpotted power supplies, or conformally coated. I also think I heard that the physical chemistry is not understood, but if it were, it might be possible to do accelerated life test. If NASA or DOD are looking to spend some money, that's one of the places, some fundamental research.

EDITOR'S NOTE: (Gap in tape---Some discussion of need to look at oxide cathodes as well as dispenser cathodes.)

KOSMAHL: Dr. Forman, at NASA-Lewis, is studying the basic processes of emission and making comparative tests of good cathodes and dead cathodes. It would be very nice to have two or three Formans.

EDITOR'S NOTE: (Suggestion to make better use, for autopsy, of failed tubes from burn-in tests.)

QUESTION: Has anyone experienced internal tube arcs, from which the tube recovers?

ILLOKEN: There are good arcs and bad arcs. Good arcs clean up the tube internally, it is not harmful; it's necessary for high-voltage tubes.

EDITOR'S NOTE: (Comment from floor that arcs should not occur in low voltage tubes, under 5600V.)

KOSMAHL: (Comment on BMEWS Klystron, 120 kV, which arced a good deal but performed well after seasoning.)

COMMENT: A redundant plea--if you want a concept of reliability, plan on it, and plan for it.

SIVO: (Comment on becoming reliant on overseas sources. Closing remarks in praise of cooperative attitude of participants.)

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